NİSAN 2025 / ÇANKIRI

CİLT: 3 SAYI: 1

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Journal of Engineering and Applied Sciences (AJEAS)

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Alfa Mühendislik ve Uygulamalı Bilimler Dergisi (AMUBD)

Alpha Journal of Engineering and Applied Sciences (AJEAS) / Alfa Mühendislik ve Uygulamalı Bilimler Dergisi (AMUBD)

International Peer Reviewed Journal / Uluslararası Hakemli Dergi
Indexed by / Veri Tabanı: Asian Science Citation Index (ASCI), Google Scholar

Volume / Cilt: 3
Issue / Sayı: 1
April / Nisan 2025
e-ISSN: 3023-6002
https://dergipark.org.tr/en/pub/ajeas

alpha
Journal of Engineering and Applied Sciences
(AJEAS)
e-ISSN: 3023-6002

Alfa Mühendislik ve Uygulamalı Bilimler Dergisi
(2025) 3/1: 1 – 14

Research Article

DOI: 10.70988/ajeas.1583799

Received: 11/14/2024

Accepted: 03/28/2025

Published: 04/30/2025

PID Controller Design in Buck Converters: Real-Time Implementation and Performance Evaluation with TMS320F28379D

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Abstract

Among the advancing technology, energy management systems and power electronics studies are becoming more and more significant day by day. Therefore, the application areas of buck converters in industrial and consumer electronics are increasing day by day. In this study, a simple and effective real-time controller for buck converters is designed and implemented. The study aims to performance the dynamic performance of the system and reduce energy losses by using the advantages of real-time control. One of the most important objectives is to reduce complex programming processes by using a model-based approach. With this model-based approach, easy changes of the system are provided with a fast intervention to the changes in the system. With the developed TMS320F28379D based real-time control approach, the stability and response time of the buck converter are tested. Simulations and experimental studies have shown that the proposed hardware and software architecture provides stable, fast and accurate results in the control of buck converters. As a consequence, this study aims to contribute to the field of power electronics by providing an effective, simple and accessible control mechanism that improves energy conversion processes. In addition, since the results obtained can be used as a reference in the design of similar systems, it is expected to be useful for both academic and industrial applications. When the voltage control of the buck converter is made for 2 Volts, the voltage change, and the duty cycle reach the desired steady state in $1.75*10^{-3}$ seconds. The results show that the proposed control structure provides a suitable and reliable solution for industrial applications. Future studies on energy efficiency and control systems will open the door to innovative designs in this field.

Keywords: *TMS320F28379D controller, Buck converter, Closed loop controller, Real-time controller*

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Buck Dönüştürücülerde PID Kontrolör Tasarımı: TMS320F28379D ile Gerçek Zamanlı Uygulama ve Performans Değerlendirmesi

Özet

Gelişen teknoloji içerisinde enerji yönetim sistemleri ve güç elektroniği çalışmaları gün geçtikçe daha da önem kazanmaktadır. Bu nedenle buck dönüştürücülerin endüstriyel ve tüketici elektroniğindeki uygulama alanları her geçen gün artmaktadır. Bu çalışmada, buck dönüştürücüler için basit ve etkili bir gerçek zamanlı denetleyici tasarlanmış ve uygulanmıştır. Çalışma, gerçek zamanlı kontrolün avantajlarını kullanarak sistemin dinamik performansını artırmayı ve enerji kayıplarını azaltmayı amaçlamaktadır. En önemli amaçlardan biri model tabanlı bir yaklaşım kullanarak karmaşık programlama süreçlerini azaltmaktır. Model tabanlı bu yaklaşım ile sistemdeki değişikliklere hızlı bir şekilde müdahale edilerek sistemin kolay bir şekilde değiştirilmesi sağlanmaktadır. Geliştirilen TMS320F28379D tabanlı gerçek zamanlı kontrol yaklaşımı ile buck dönüştürücünün kararlılığı ve tepki süresi test edilmiştir. Simülasyonlar ve deneysel çalışmalar, önerilen donanım ve yazılım mimarisinin buck dönüştürücülerin kontrolünde kararlı, hızlı ve doğru sonuçlar verdiğini göstermiştir. Sonuç olarak bu çalışma, enerji dönüşüm süreçlerini iyileştiren etkili, basit ve erişilebilir bir kontrol mekanizması sağlayarak güç elektroniği alanına katkıda bulunmayı amaçlamaktadır. Ayrıca elde edilen sonuçlar benzer sistemlerin tasarımında referans olarak kullanılabileceğinden hem akademik hem de endüstriyel uygulamalar için faydalı olması beklenmektedir. Buck dönüştürücünün gerilim kontrolü 2 Volt için yapıldığı zaman, geriliminin değişimi ve doluluk oranının $1{,}75*10^{-3}$ saniyede istenilen kararlı hale ulaşmaktadır. Sonuçlar, önerilen kontrol yapısının endüstriyel uygulamalar için uygun ve güvenilir bir çözüm sağladığını göstermektedir. Enerji verimliliği ve kontrol sistemleri üzerine gelecekte yapılacak çalışmalar bu alanda yenilikçi tasarımlara kapı aralayacaktır.

Anahtar kelimeler: *TMS320F28379D denetleyicisi, Buck dönüştürücü, Kapalı çevrim denetleyici, Gerçek zamanlı denetleyici*

Citation: G. Gorel, Y. Bektes, F. Korkmaz, H. Ozkaya, “PID Controller Design in Buck Converters: Real-Time Implementation and Performance Evaluation with TMS320F28379D”, AJEAS. (2025) 3(1): 1-14. http://dx.doi.org/10.70988/ajeas.1583799

1. Introduction

Energy efficiency is one of the important issues of sustainable development today. Energy saving during production, transmission, distribution and consumption is important in terms of economic gain and reducing negative impacts on the environment. Especially in industrial areas, energy efficiency enables better use of resources and lower costs by optimizing business processes. In addition, increasing energy efficiency facilitates the integration of renewable energy sources and reduces fossil fuel dependency. Considering all these situations, the development and implementation of energy efficiency strategies is an important need at individual and societal levels [1]. Therefore, energy efficiency should be the most important goal for a sustainable future.

The improvement of energy conversion systems, frequently used in developing technology, has become an essential subject of study in electronic system design. Buck converters' role and usage area in modern power electronics are increasing daily. Buck converters work primarily based on the cycle of energy storage and release by the switching process. They generally work with inductive and capacitive elements to provide efficient current and voltage control. In addition, using advanced algorithms to control these systems helps obtain the desired output values by reducing cyclic voltage and current errors. The efficiency of the control systems of these transducers plays a vital role in energy efficiency and system performance [2]. When optimal control algorithms are implemented, the stability of the system increase, and energy losses are reduced with the ability to react quickly to dynamic load conditions.

Optimal control of buck converters is crucial for the system's efficiency, stability, and dynamic response time. Software-based control technologies, especially with integration of the digital control algorithms, improved the performance of buck converters [3]. PID control is a widely used method to reduce losses and optimize system response. In addition, improved adaptive control strategies and fuzzy logic-based methods offer effective solutions for adapting to variable load conditions. Modern microcontrollers provide high processing power and allow real-time implementation of complex control algorithms [4-5].

The selection of the optimum control method is very important to improve system performance and achieve the targeted output. Especially in buck converters, these applications significantly impact the system's stability and throughput. Among the important criteria in determining the performance of control systems, factors such as dynamic response time, control cycle speed and algorithm complexity draw attention. While the dynamic response time shows how quickly the system can respond to instantaneous changes; control cycle speed is essential for continuous monitoring and control. On one hand dynamic response time indicates the speed with which the system can react to instantaneous changes; control cycle speed is essential for continuous monitoring and control. Moreover, the control method can also influence both application integration and system load thereby being inherently related to overall reliability and performance [6]. Thus, it goes without saying that we must account for such features in a control application design as well.

In applications where efficiency is important, such as Buck converters, real-time operation of control algorithms reduces energy losses and improves system performance. Advanced control units, such as TMS320F28379D microprocessor boards, ensure that these systems operate with the desired precision. Increased reliability and efficiency lead to a smoother progression of industrial automation processes, since new features are added with real-time control. This field of engineering (real-time control system) has become an important topic in research and development [7].

This study aims to develop a new approach by offering alternatives to traditional methods of controlling buck converters. Thus, the findings obtained are hoped to contribute to academic literature and be a valuable reference for industrial applications. In addition to all these contributions, it also contributes to simple programming in universities and academic education. The main purpose of the controller to be developed is to increase the efficiency of buck converters and reduce energy losses. In this context, the design of real-time control algorithms is important to improve the system's dynamic response and ensure its stability. In addition, good use of the features offered by TMS320F28379D microprocessor card is critical to improving the overall performance of the system. The research aims to examine the integration of this controller with real-time operating systems and the challenges encountered in software development processes. As a result, the analysis of the data obtained is necessary to evaluate the performance of the developed system and, thus, to ensure its suitability for industrial applications [8]. These findings will contribute to the literature on optimizing energy efficiency and control strategies.

2. Buck Converters

Buck converters are effective and efficient basic electronic circuit elements used in the conversion of dc-dc voltage levels. These converters use high frequency switching to reduce the input voltage to a desired output voltage. The selection of components used in the design of the conversion system is critical; Suitable capacitors and inductors increase the stability of the system, ensuring sustainable control. The switch controls the output voltage level by turning on and off at high frequency, while the inductor stores this energy and balances the output voltage. In particular, the switching frequency directly affects the efficiency and heating status of the system. The capacitor at the output provides a smoother output voltage by preventing surge. The dynamics and stability of the parameters involved play an important role in the development of control strategies of Buck converters. Therefore, understanding these basic principles is very important for the realization of an effective control system [9].

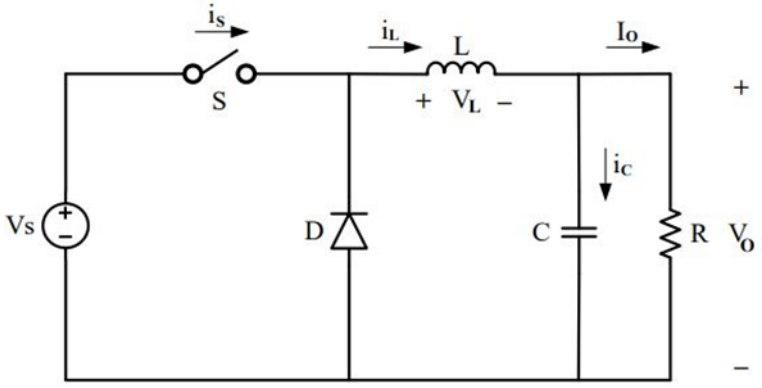

Figure 1. DC-DC step-down converter circuit diagram

Figure 1 shows the step-down converter circuit. A resistor (R) is attached to this arrangement, acting as a circuit load. In addition, it refers to power electronic circuit elements such as inductor (L), capacitor (C), input source (Vs), output voltage (Vo), and diode (D) in the circuit. The circuit operates in two modes. The first mode is the mode in which the S switch is off, and the other is the mode in which the S switch is on. Output current (Io), inductor current (I_L), capacitor current (I_C), switch current (I_S) waveforms are shown in Figure 2.

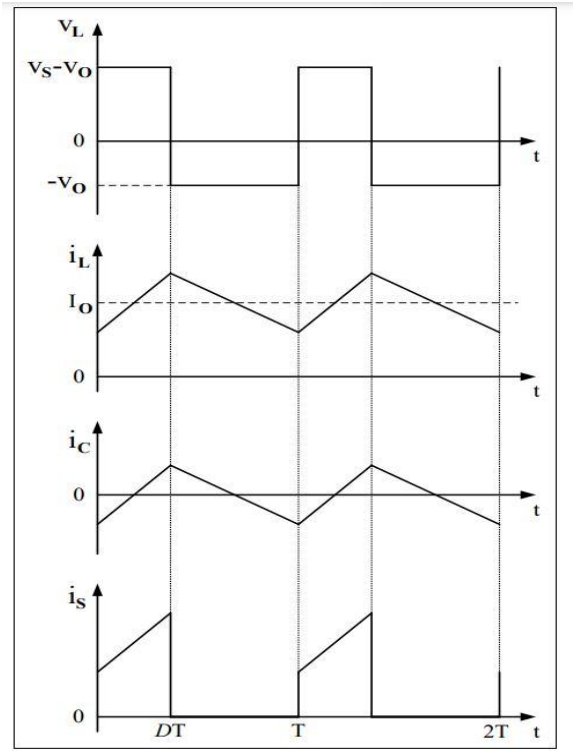

Figure 2. Waveforms generated on the converter elements.

3. PID Controllers

For systems that include a control structure, it is important to select a control circuit suitable for the system structure. PID control, which is one of the closed loop control structures, is preferred in applications due to its simple use, applicability, and high precision. PID control provides the system error by taking the difference between the voltage value obtained at the output of the system and the reference voltage value desired to be obtained at the output. This error value is recalculated with proportional (P), integral (I) and derivative (D) effects and the system output is adjusted to the lowest value and the system output is adjusted to the voltage closest to the reference voltage value. In PID control systems, and are the coefficients used to apply proportional, integral and differential effects on the system, respectively. The continuous time expression of the control system is given by Equation 1 and the transfer function is given by Equation 1. PID control controller block diagram is shown in Figure 3.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

$$G(s) = K_p + \frac{K_i}{s} + K_d s \quad (2)$$

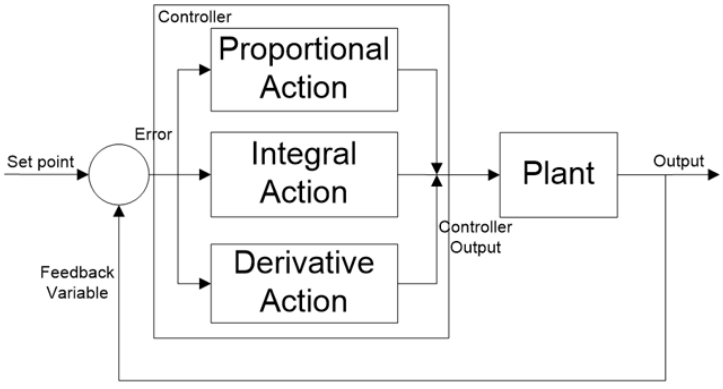

Figure 3. PID control controller block diagram

4. TMS320F28379D Microprocessor Overview

TMS320F28379D structure is a microcontroller platform that is made for advanced control systems and stands out with its fast calculation features. This microcontroller comes with a 32-bit DSP structure and offers high processing speed and multitasking capabilities. In addition, integrated advanced analog-to-digital (ADC) converter and digital signal processor (DSP) units are essential for real-time control applications. These features make it useful to use closed loop control algorithms to ensure high precision and efficiency, especially in power electronics applications such as buck converters. The expansion paths used and the many options it offers in terms of numerical control engineering increase the flexibility of the system design and ensure cost-effectiveness [10]. Overall, TMS320F28379D structure is an important tool for developing effective and efficient control solutions in both industry and academia.

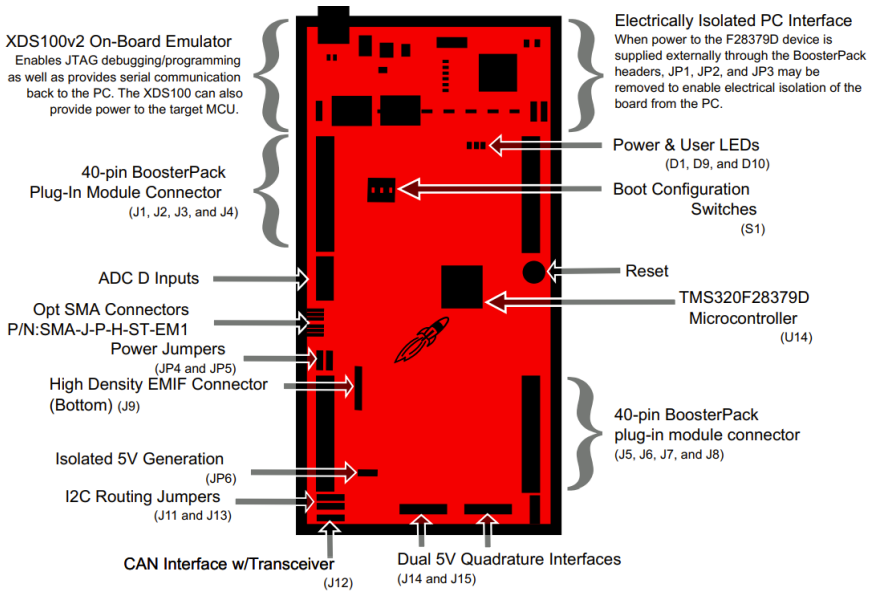

Figure 4. LaunchXL- F28379D Overview

Figure 4 shows the overview diagram of the Launchxl-F28379D microcontroller and includes figural information about the circuit elements on the board such as connectors and jacks.

Programming environments and tools, especially in complex systems such as the buck converter, the selection of appropriate development tools is critical to performance and efficiency. TMS320F28379D microcontroller board offers a platform suitable for such applications with its highly integrated structure and flexible programming options. At this point, the choice of software development environment is important both in terms of providing user-friendly interfaces and meeting the real-time control needs of the system. In addition, the tools used in the simulation and testing phases of the developed control algorithms have a great impact on improving performance [11]. In this study, a Matlab/Simulink-based software development infrastructure was used, and thanks to the full compatibility of the control card with the program, a simple and efficient experimental environment was created.

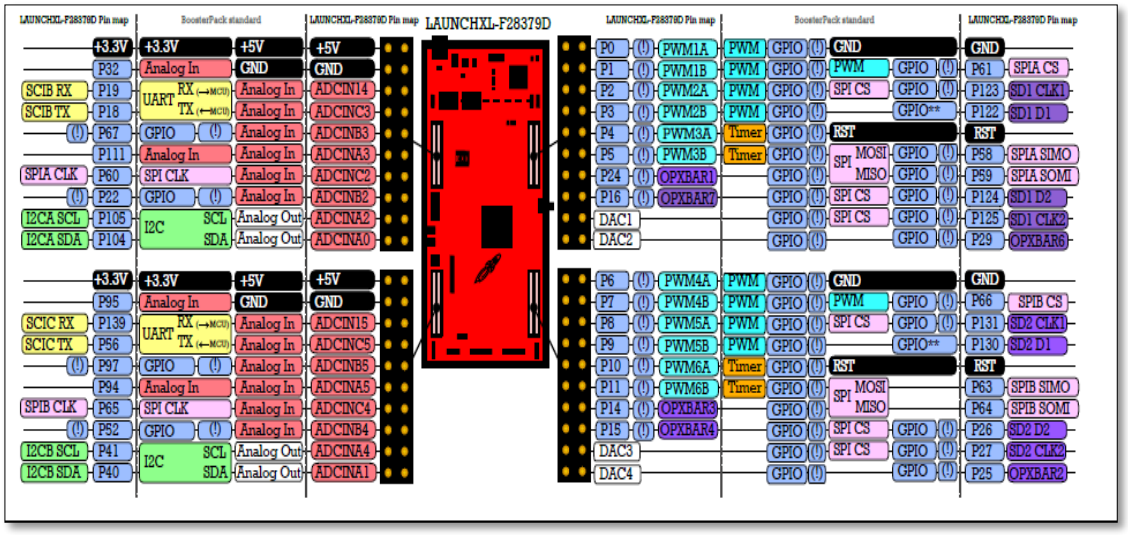

Figure 5. TMS320F28379D microcontroller pins

The TMS320F28379xD has four different analog digital converters (ADCs) on the microcontroller. Many analog signals can be controlled with 16-bit and 12-bit resolution. The F28379xD can be easily connected and communicated with the host computer. Figure 5 shows pinout diagram of the Launchxl-F28379D microcontroller.

5. System Modeling and Simulation

Systems modeling and simulation play a key role in understanding and enhancing complex systems. This approach represents the physical world through mathematical and logical expressions enabling us to examine various scenarios. Modeling dynamic behavior proves crucial to develop real-time control strategies in energy conversion systems like the buck converter. The modeling stage involves a detailed description of the system's core components and interactions, while the simulation tests this model's performance under different conditions. These techniques help to design and put into action more effective control algorithms, which leads to increased energy efficiency and better overall system performance. System modeling and simulation have a significant impact on engineering applications paving the way for groundbreaking solutions and long-lasting system designs.

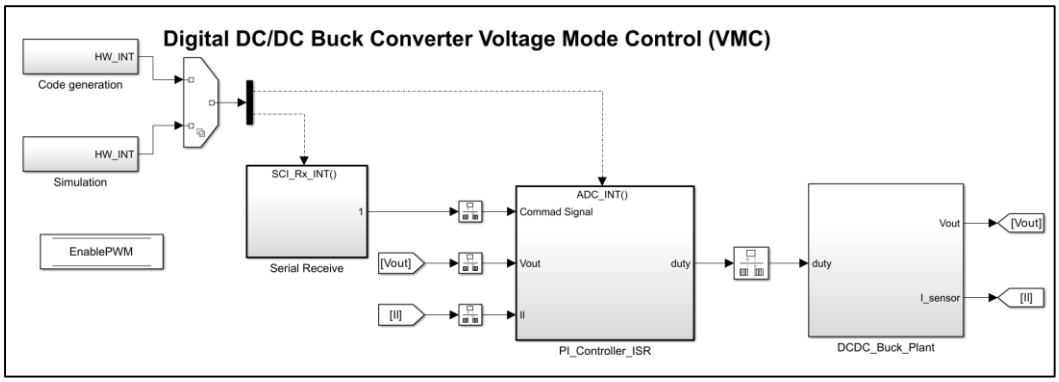

Figure 6. Main simulation circuit

In line with the main simulation circuit in Figure 6, the Simulink file was first run as a simulation for 0.01 seconds. Since it was operated using the simulation option in the simulink environment, the DC-DC step-down circuit was operated in the simulation environment using the Simelectronics circuit elements in Figure 7 and Figure 8.

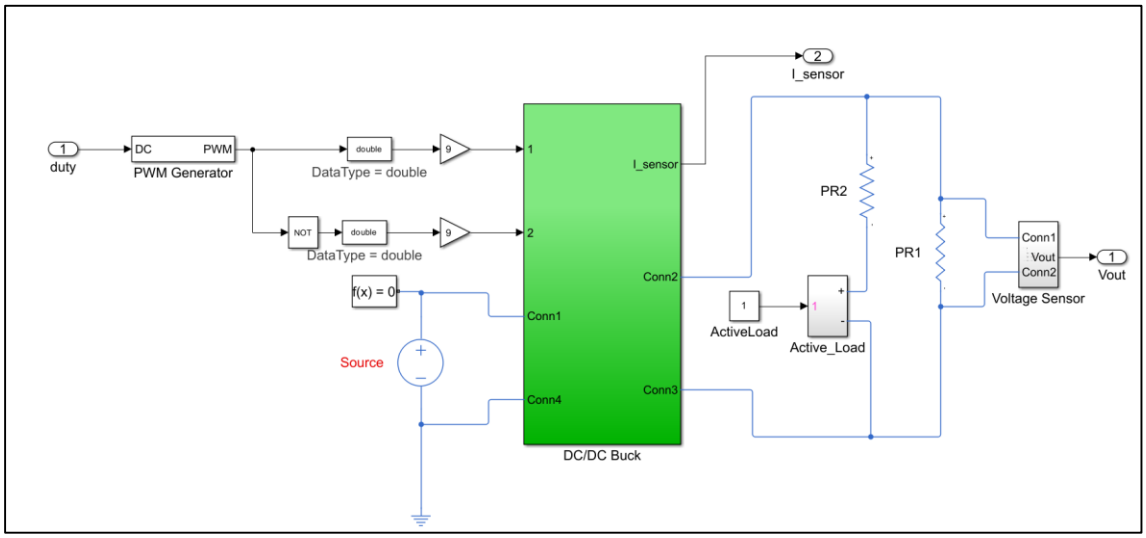

Figure 7. Simulink® circuit of the DA-DA converter

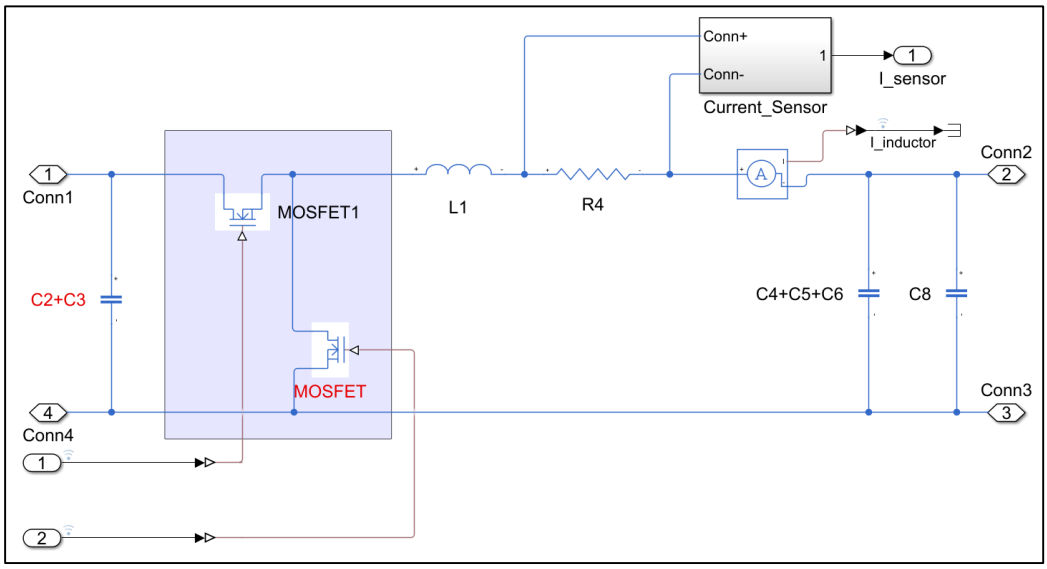

Figure 8. Detailed Simulink® circuit of the DA-DA converter

In order to run the simulation circuit, the P parameter was first determined as 0.1 and the I parameter as 0.008. The Vout output voltage is determined as 2V. The reference results of the DC-DC converter operated according to the Vout voltage are shown in Figure 9.

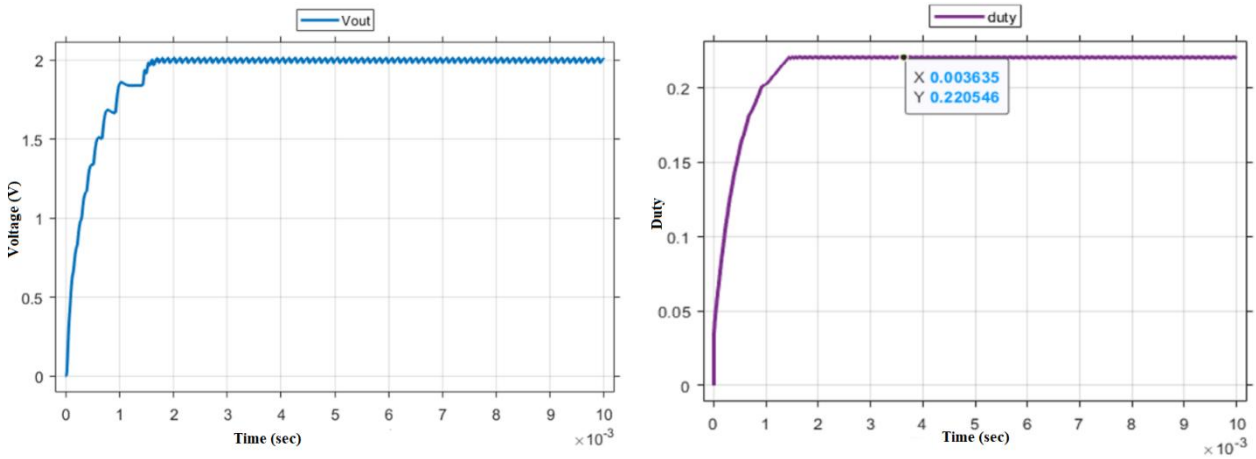

Figure 9. Change of Vout output voltage and fill rate

For the case where the output voltage of the step-down converter is determined as 2 Volts, the change of the Vout voltage and the time-dependent change of the duty cycle are shown in Figure 9. As shown in Figure 9, it reaches the desired voltage value in $1.75*10^{-3}$ seconds.

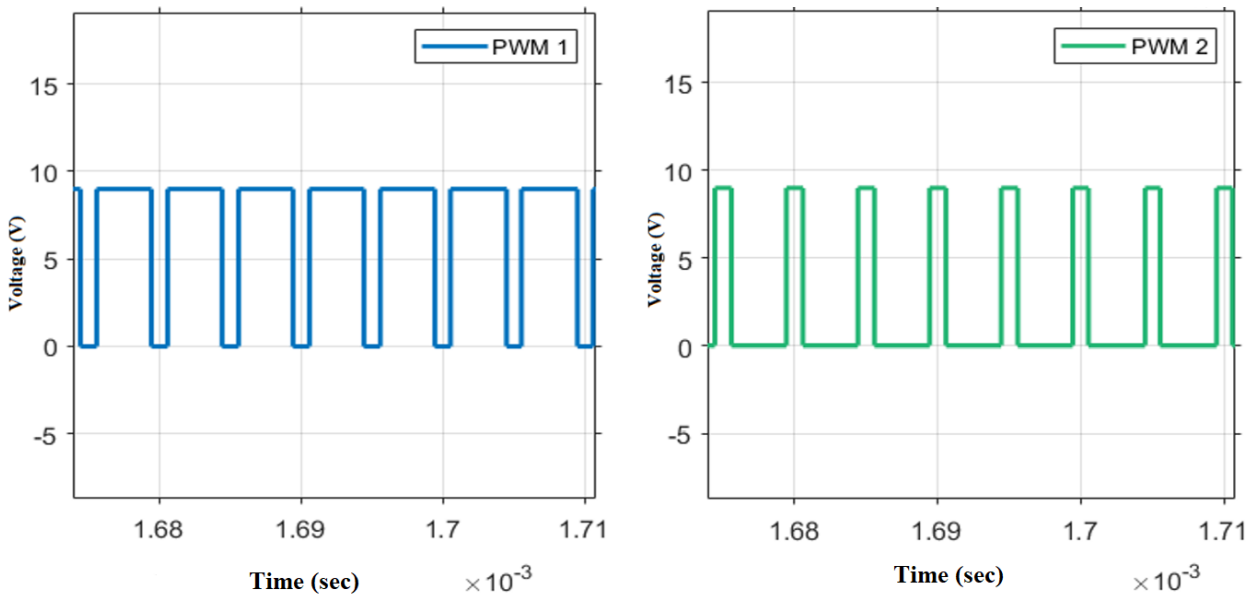

Figure 10. MOSFET elements PWM switching signals

PWM signals, in which the two mosfets in the DC-DC step-down converter circuit are switched at opposite times to each other, are shown in Figure 10.

According to the switching times of PWM signals, the current direction of the circuit inductor changes. This change is shown in Figure 11. It has been observed that the descending edge time and rising edge times in this figure are one-to-one compatible with PWM signals.

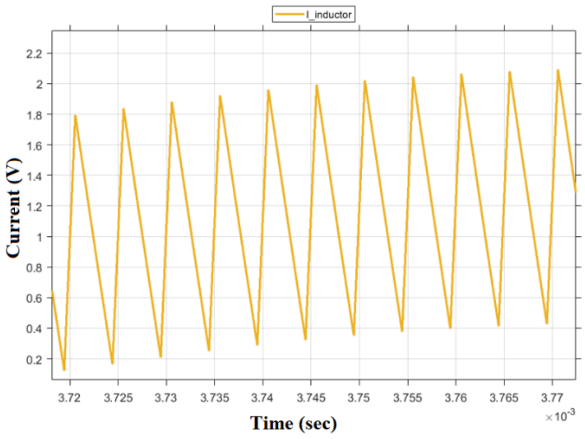

Figure 11. Time-dependent variation of inductor current

6. Experimental Studies

Hardware design is known to have a significant impact on real-time control systems. At every stage of design, the selection of hardware components is critical to improve the system's performance. TMS320F28379D In the design of the buck converter with the microcontroller, the processing capabilities of the microcontroller, as well as the speed at which the analog-to-digital converters (ADC) will operate, and the design of the power management circuits should be carefully considered. In this context, the operation of hardware components with minimal latency is very important for energy efficiency and overall system reliability, increasing the fast response time of the control system. Therefore, optimizing hardware design in the light of theoretical knowledge is a factor that directly affects the application's success.

TMS320F28379D, the application assembly is installed using the microcontroller and the Bootxl-BuckConv step-down converter, as shown in Figure 12.

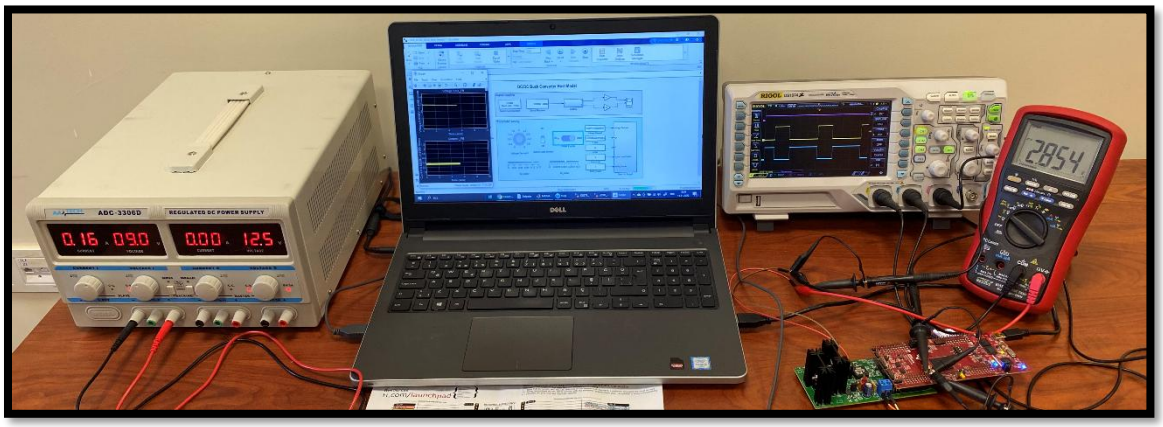

Figure 12. Test setup set up for experimental studies

A 9-volt DC power supply was used as the input source, an Oscilloscope was used to see the mosfet switching signals, and a multimeter was used to measure the output voltage of the DC-DC step-down converter. After the model-based circuit TMS320F28379D in the Simulink environment was programmed on the Microcontroller card.

When the step-down controller is operated under the specified parameters, the desired value of 2.8 is obtained, and the result and the PWM signals produced by the control card for the mosfets to achieve this result are shown in Figure 13.

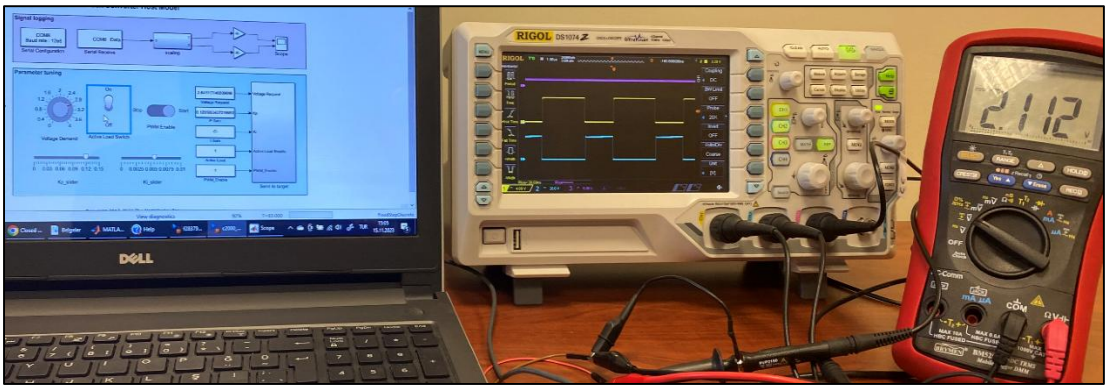

Figure 13. Application device installed by applying active load

In the designed circuit, the DC-DC step-down converter card has different options for static load and active load. The results obtained in the first part of the experiment were obtained with a constant resistance load of 7.5 ohms. A software-controlled active load of 2 ohms can be applied to the circuit when the load switch is changed to active load from the setting window. As in Figure 14, results with different characteristics can be obtained.

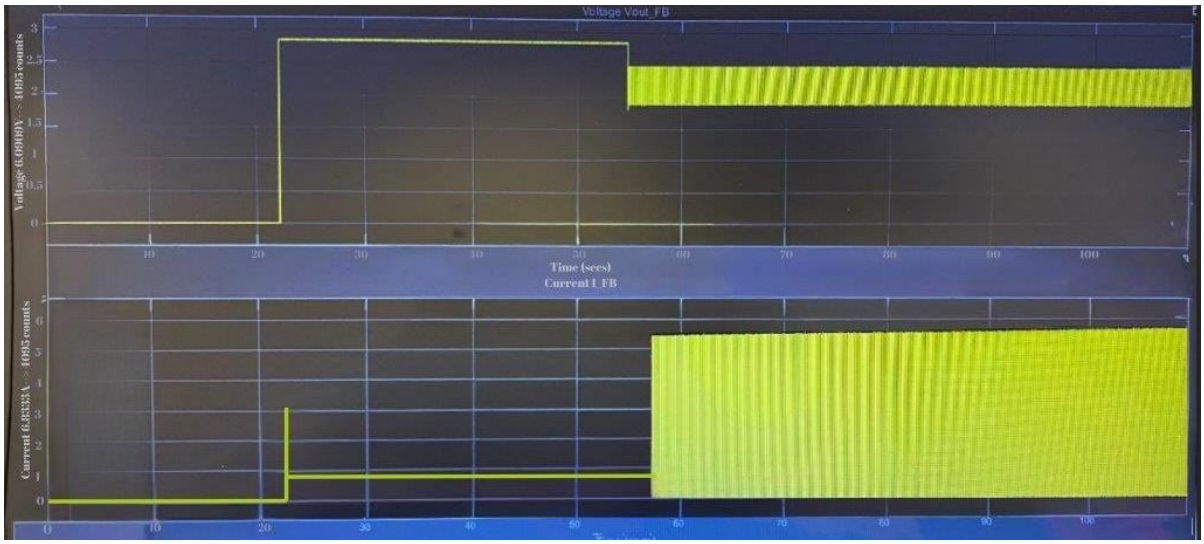

Figure 14. Active load switch graph

When voltage is applied to the application device, the adjustment window is suitable for replacement. To see the effect of active load on output variables, the results were observed by turning off (engaged) the active load switch at 55 seconds of the results in Figure 14.

7. Results and Discussion

TMS320F28379D control of the Buck converter with a microprocessor card has significantly improved performance by finding the set parameters. In this context, the effects of the applied PID control algorithm on system dynamics were examined, and the results obtained were compared with

those of theoretical modeling. The results show that the proposed control structure offers a suitable and reliable solution for industrial applications. In addition, the data obtained in future research is expected to form a basis for developing more complex control strategies.

TMS320F28379D microprocessor card is a frequently chosen solution in this field and stands out with its powerful processing capacities and different integrated features. Improving the hardware-software interfaces increases the real-time performance of the algorithms, enabling the power converters to work more precisely and reliably. In addition, combining control algorithms with hardware reduces the processing load and increases the system's overall efficiency. A good integration process is an essential step in the design of power systems and paves the way for more sustainable energy solutions.

8. Conclusion

Today, the combination of control algorithms with hardware plays an important role, especially in power electronics. This process enables the control systems to offer high efficiency, fast response time, and better stability. The study covers the design and implementation of a real-time controller for a voltage reducer (buck) converter with an effective PID controller combined with simple, inexpensive hardware using the TMS320F28379D microcontroller board. The application with the Microcontroller Board was carried out to analyze the voltage regulation capability, dynamic response time, and overall efficiency of the buck converter system. In the implementation phase, firstly, the control algorithm and the transducer model were tested based on hypotheses in the simulation environment. These simulations allowed for early detection of possible errors and corrective measures to be taken. In addition, model-based design enables more flexible and improvable methods. Subsequently, an experimental setup with real-time monitoring and control was established. The performance of the system under actual test conditions was compared with the simulation results, and the effects of all variables on the system were examined. In the study, the performance of the control algorithm was tested and evaluated under different load conditions. The results are promising because the system remains stable and reacts quickly over a wide operating range. In addition, controller design have been shown to play an important role in improving system efficiency. The created control setup to improve control performance is important as it can also be used for more complex systems. As a result, the data obtained not only confirms the success of the application but also serves as the basis for further studies. In addition, the simplicity of the implemented algorithms, combined with a user-friendly interface, shows that the system offers vast application potential. Future research should investigate how the proposed control structure can be applied in more complex energy management systems, and the asynchrony of existing systems should be corrected. These findings aim to contribute to the relevant literature by allowing wider control system design applications.

Symbols

ADC Analog digital converter
DC Direct current
DSP Digital sinyal processor
PID Proportional Integrator Derivative
PWM Pulse width modulation

Acknowledgments and Funding

The authors would like to thank Çankırı Karatekin University Scientific Research Project Unit for provision of funding with the Project MF240223L05. The authors thank the Electrical-Electronics Laboratory at Çankırı Karatekin University for supporting our experiments.

Declarations and Ethical Standards

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Author Contributions

Goksu Gorel conceived of the presented idea. Yahya Bektes and Hakan Ozkaya developed the theory, performed the computations and carried out the experiments. Fatih Korkmaz supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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alpha
Journal of Engineering and Applied Sciences
(AJEAS)
e-ISSN: 3023-6002

Alfa Mühendislik ve Uygulamalı Bilimler Dergisi
(2025) 3/1: 15 – 34

Research Article

DOI: 10.70988/ajeas.1591897

Received: 12/03/2024

Accepted: 01/22/2025

Published: 04/30/2025

New Generation Minimized Flow Resistance Butterfly Valve Design

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Abstract

Butterfly valves get this name because the visual of their working principle resembles the wing movements of a butterfly. In this way, flow control is more ergonomic, and it becomes possible to save water. However, in addition to these advantages, the difficulty of minimizing flow resistance is observed as a disadvantage. The costs of design improvements made in valve products, which are produced by the casting method and involve labour-intensive production stages such as assembly and welding, are quite high. In these cases, computer-aided design and test simulation become more important. In this study, the designs of the products were carried out by using computational fluid dynamics and finite element methods. Details of the simulations and design verification stages were included, the designs were made with Solidworks and these data were validated by ANSYS. As a result of the study, a body and ring designs were achieved with an improvement of 26% compared to existing products and 32% compared to the industry average. Finally, national and international patent applications have been made for the unique curved body and gradual shaft designs obtained during the development phase of the product.

Keywords: *Valve design, Simulation, Flow resistance, Water save.*

Yeni Nesil Minimize Edilmiş Akış Dirençli Kelebek Vana Tasarımı

Özet

Kelebek vanalar, çalışma prensibine ait görselliğin bir kelebeğin kanat hareketine benzemesinden dolayı bu ismi almıştır. Bu sayede akış kontrolü daha ergonomik olmakla birlikte su tasarrufu da sağlanmış olur ancak bu avantajların yanı sıra akış direncini en aza indirmenin zorluğu da bir dezavantaj olarak görülmektedir. Döküm yöntemiyle üretilen ve montaj, kaynak gibi emek yoğun üretim aşamalarını içeren vana ürünlerinde yapılan tasarım iyileştirmelerinin maliyetleri oldukça yüksektir. Bu gibi durumlarda bilgisayar destekli tasarım ve test simülasyonu daha da önem kazanmaktadır. Bu çalışmada hesaplamalı akışkanlar dinamiği ve sonlu elemanlar yöntemleri kullanılarak ürünlerin tasarımları gerçekleştirilmiştir. Simülasyon ve tasarım doğrulama aşamalarının detaylarına yer verilmiş olup, tasarımlar Solidworks ile gerçekleştirilmiş ve bu veriler ANSYS ile geçerli kılınmıştır. Çalışma sonucunda mevcut ürünlere göre %26, sektör ortalamasına göre ise %32 iyileşme sağlayan bir gövde ve klape tasarımı elde edilmiştir. Son olarak ürünün geliştirme aşamasında elde edilen özgün kavisli gövde ve kademeli mil tasarımları için ulusal ve uluslararası patent başvuruları yapılmıştır.

Anahtar kelimeler: *Vana tasarımı, Simülasyon, Akış direnci, Su tasarrufu.*

Citation: E. Özkan, "New Generation Minimized Flow Resistance Butterfly Valve Design", AJEAS. (2025) 3(1): 15-34. http://dx.doi.org/10.70988/ajeas.1591897

1. Introduction

According to current research, it was determined that annual water consumption the ratio is 800 m^3/person [1]. 2.3 billion people are trying to continue their lives by completely deprived of drinking water [2]. According to the similar studies, the number of countries that will have problems regarding to reach the water and survive under these conditions up to 54 by 2050 [3]. By considering these data, the world population will be expected to reach approximately 9.4 billion and it is predicted that 40% of them will not be able to benefit from the drinking water [4]. Therefore, it is inevitable to use water resources effectively and prevent waste [5]. For this purpose, fluid transportation and storage systems reducing water loss to minimum levels become mandatory [6]. The valve designed to ensure this decreasing flow resistance in systems is of importance [7]. Making these designs is a quite costly process [8]. For this reason, computer-aided design and simulation programs are used [9].

Computational Fluid Dynamics (CFD) is considered a sub-branch of fluid mechanics and caused from liquids problems using numerical algorithms by providing analysis [10]. CFD method is used as an identifiable simulation tool [11], especially in processes involving flow such as liquid/gas [12]. This method is often used to determine the operating modes of all types of functions and convection [13], which includes flow, heat-mass movements [14]. But every fluid by using time analytical methods may not be possible to determine the behaviour, and numerical methods can be used to solve this problem [15]. Analytical methods are generally based on mathematical functions [16]. Numerical methods are used when producing solutions in the form generally provides numerical results [17]. The results calculated using these methods are very close to the real values and can be adjusted to the desired level [18]. In cases where it is desired to increase the sensitivity of the results the number of operations that need to be solved by the computer is increasing [19]. Hence this takes a long time, that causes both calculation times to increase and the computer to work inefficiently [20]. On the other hand, these simulations are used in the design of butterfly valves, where fluid behaviour is investigated and increasingly used in the industry, have become more important [21].

Butterfly valves have been designed to control fluid systems within the time specified in the parameters on preventing the movement [22, 23]. Possible damage to the valve carries risks such as leakage, cracks and explosion with material contamination and loss [24]. More importantly leaks in the system, such as poisoning and fire cause dangerous situations to occur [25]. Butterfly valves should be preferred to prevent such situations [26, 27]. The biggest advantage of butterfly valves on the application is providing high flow rates compared to its dimensions [28]. This issue becomes important especially when there is a lack of space in controlling chemical fluids [29]. Therefore, these products are commonly preferred in the systems, that contain chemicals, wastewater and distribution networks [30-34].

The motivation that started this study was reducing the friction on the ring surface of the butterfly valves with an original design that cause to achieve energy efficiency. For this purpose, first the target properties of the products exposed to the fluids have been defined, then the dynamics calculations, simulation studies, computer-aided design and prototype manufacturing processes have been carried out, respectively. The valves used in this study were designed to comply with EN GJS 400-18 LT standard. Moreover, the raw materials were selected to fulfil the TS EN 1267 standard requirements. The prototype with process and flow line design simulation was adjusted according to the EN 1074 with the scope of drinking water, distribution lines, industrial applications, water treatment facilities, pump stations, industrial waste systems. When literature studies were evaluated, pipelines against high stresses that may occur resistant must meet the EN GJS 400-15 (also known as GGG 40) standard requirements, so simulation-supported analyses with the defined materials and prototype production activities were carried out with this purpose. Finally, the original curved for body and stepped shaft

designs have been performed, successfully. Moreover, a national and an international patent application have been made.

2. Methodology

2.1. Computational fluid dynamics

CFD is an analysis method, which is widely used in the valve industry. In this way, the flow conditions of the valve are able to simulate by using various equations that describe 3D flows. It is very important for designers to have all analyses results carried out before prototype production. It is possible to do all in a virtual environment and causing to do everything right in the first time with less labour and material loss. Thanks to this, it can be transferred economically in a short time to mass production of the product. The three-dimensional designs of products have been carried out by using Solidworks drawing program. ANSYS computer aided simulation program has been used for CFD analysis and FEA. Butterfly valve with a diameter of 200 mm, and 1000 mm were chosen as sample to do the experimental verifications of the study. As in applications 16 bar value most chosen, the nominal pressure was selected as the same and defined like PN16. While CFD analysis carried out, K-epsilon turbulence model was solved by keeping the y+ value at 3 and below. The limit in the layers (boundary layers) and the mesh improvements have been made during the process.

Flow coefficient and pressure loss coefficient formulas were defined according to EN 1267:2012 (E) standard. Accordingly, the flow coefficient (Kv) is calculated with Equation 1.

$$Kv = Q\sqrt{\rho \div (\Delta p \times \rho_0)} \quad (1)$$

In the equation, Kv (m^3/hour) is the flow coefficient, Q is the flow rate in m^3/hour, ρ is the density of water in kg/m^3, ρ_0 is the density of water in kg/m^3 at 15 °C, Δp expresses the pressure loss in the valve (difference between inlet and outlet pressure).

2.2. Finite element analysis

The valve was designed in FEA complies according to the EN 1704 standard, where the boundary conditions defined in the strength values. During the FEA phase the parts were presented in two different numerical formats such as single and assembled. However, Rayleigh-Ritz method was performed for the interpolation solution. The specified boundary conditions were applied exactly as defined in the standard. One and a half times the nominal pressure value for the body, ten percent of the nominal pressure value for the ring part defined as excess. As a result, obtained from this part, the material analysis and selection stage should take place.

2.3. Materials selection

The valve model includes 2 parts. First part is body that is in contact with the fluid and material selection of the body is defined in TS EN 12266 and TS EN 1074 standards. According to these standards body part must be high strength against the one and half times pressure. As a result of analyses made according to standards the body material that can withstand the damage was chosen. The material of the ring was also chosen by the same method with one small difference. As defined in the standards, the selection materials for the ring are that can withstand ten percent more than pressure value. The ring strength analysis has been made according to stress and deformation results. As a result of evaluation for all these data EN GJS 400-15 (also known as GGG 40) material has been defined and selected. This material matched according to the finite element mechanical analysis outputs, too. The stresses in the system were discussed and analysed in a virtual-simulated environment. Hence, product

and process design were carried out. 24 bar pressure was defined on the surfaces of body fluid contact as a result of finite element analysis. The maximum amount to be applied to body surfaces pressure values are shown in Fig.1.

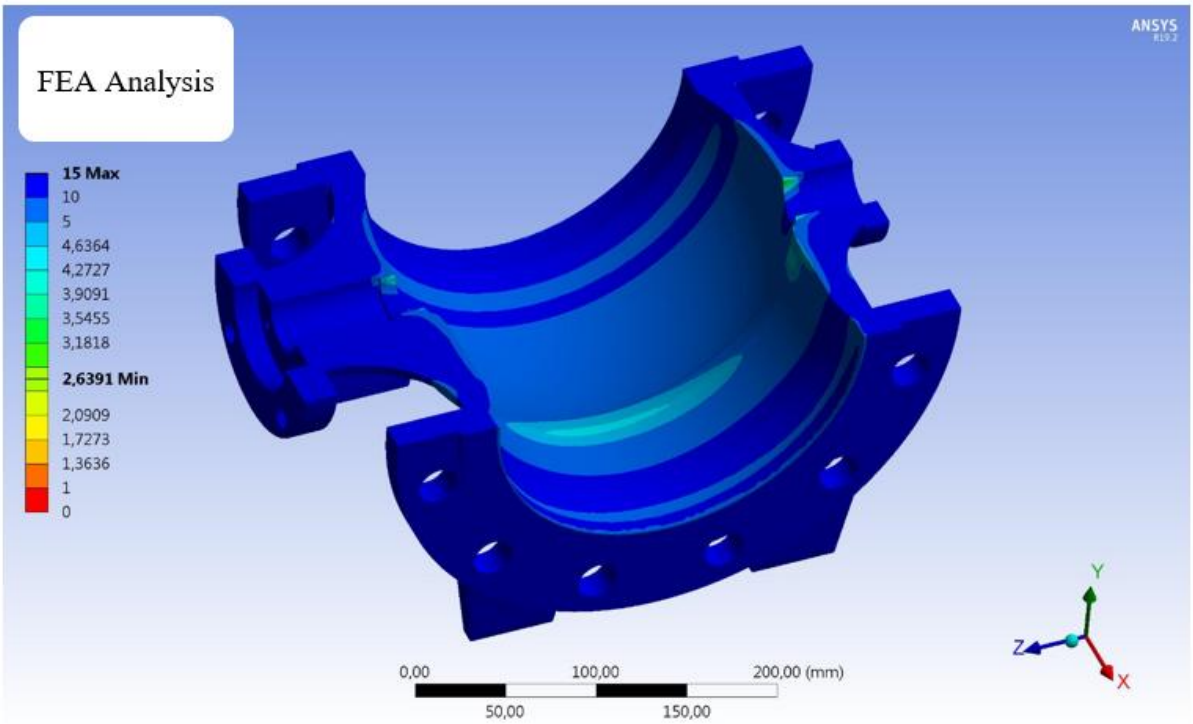

Figure 1. The highest-pressure load defined on the surface for finite element analysis

As the low melting temperature, suitable for prototype production fluidity, easy casting, ease of machinability, high strength with high wear resistance, and high ductility properties, EN GJS 400-15 material caused to accelerate the process. Thanks to numerical simulation applications, material load-stress distributions on operations dimensional changes and similar metallurgical and mechanical properties at different parameters can be revealed before the prototype production. According to the analysis of equivalent stresses on body design, verification process has been carried out. One and a half of the nominal pressure of 16 bar for the solid that can operate under 24 bar pressure was applied on the body by the mechanical analysis as shown in Fig. 2.

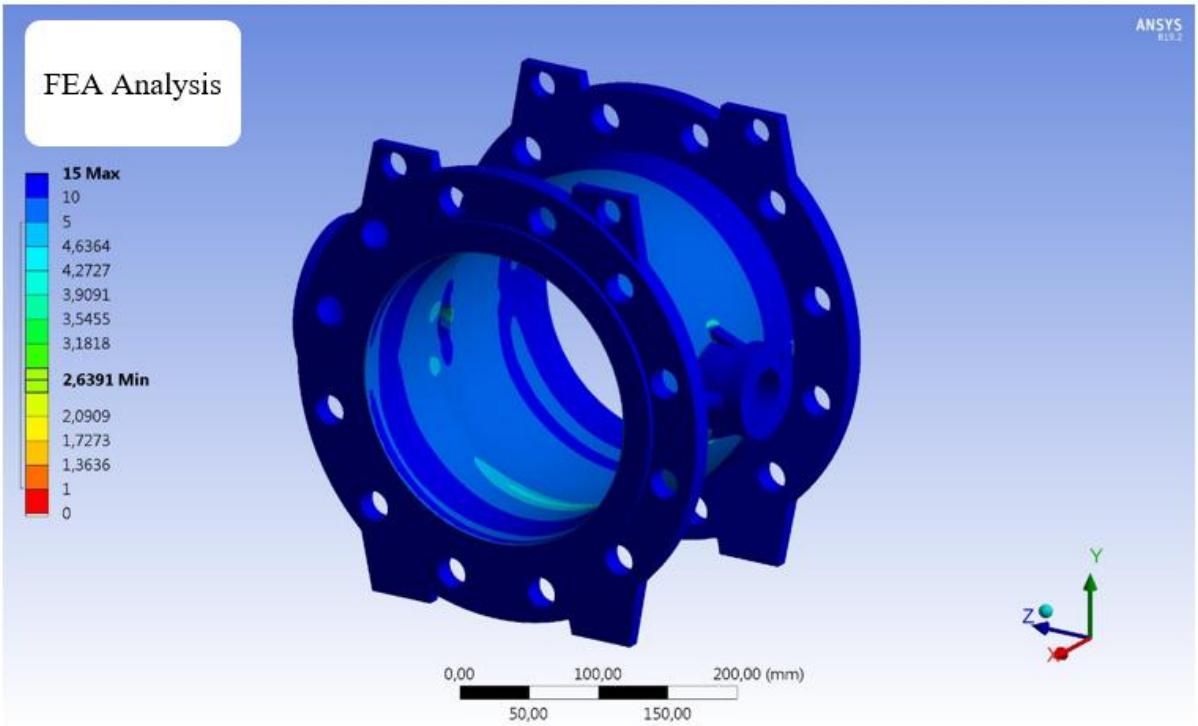

Figure 2. Mechanical analysis of the material selected for the body design under 24 Bar pressure

240 MPa yield strength value has been considered as ten percent more than nominal stress for realized ring materials mechanical tests by using numerical analysis method. Accordingly, 1.1 times more of the maximum working pressure (16 bar) was defined as 18 bar for the ring as shown in Fig. 3.

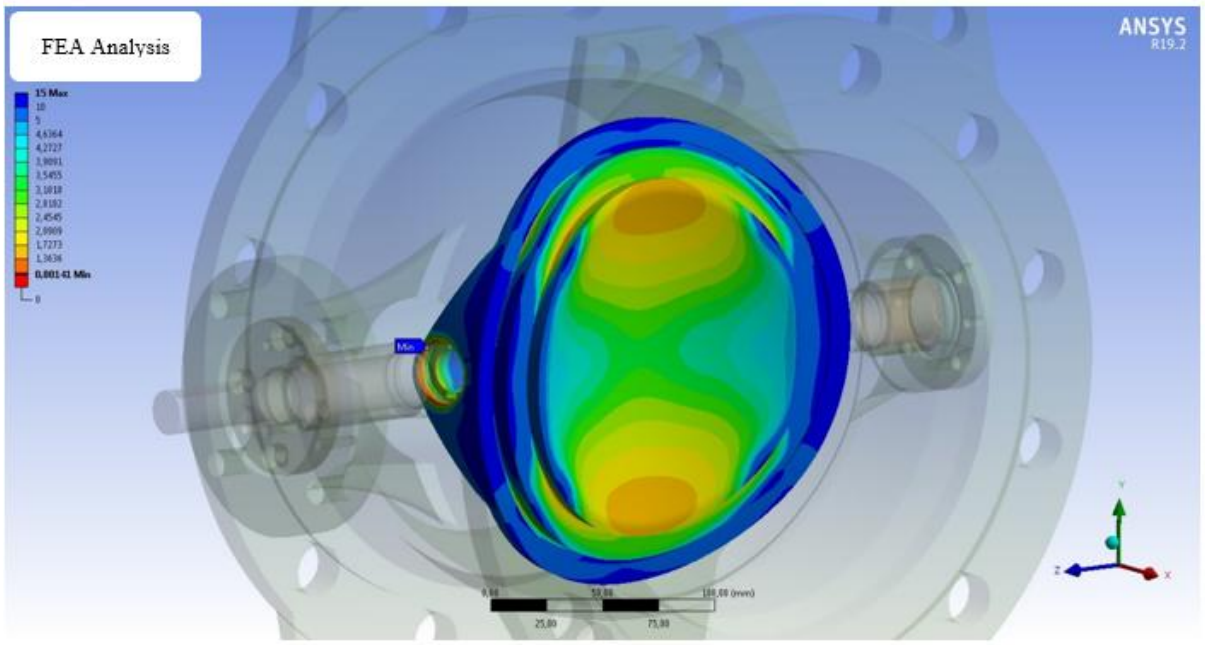

Figure 3. Mechanical analysis of the ring assembled on the body and operating under 1.1 times the nominal pressure value

2.4. Flow simulations

CFD analyses for the products designed with EN GJS 400-15 material were carried out under 16 bar pressure, 4m/s flow rate and with the valve in the fully open position by using finite element method. Fig. 4 shows the general view of CFD for disc component.

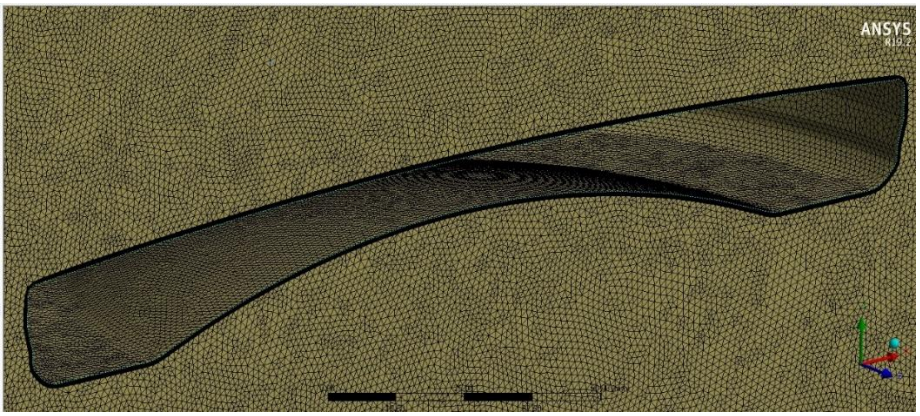

Figure 4. Mesh analysis of the disc performed by CFD

A mesh independence test was performed to prove that the results of the mesh analysis performed were reliable. Fig. 5 shows the corresponding graphic. Accordingly, the volume flow rate was determined as 116,14569 at element number 8.000.000 and the value was 116,15249 at element number 9.234.500.

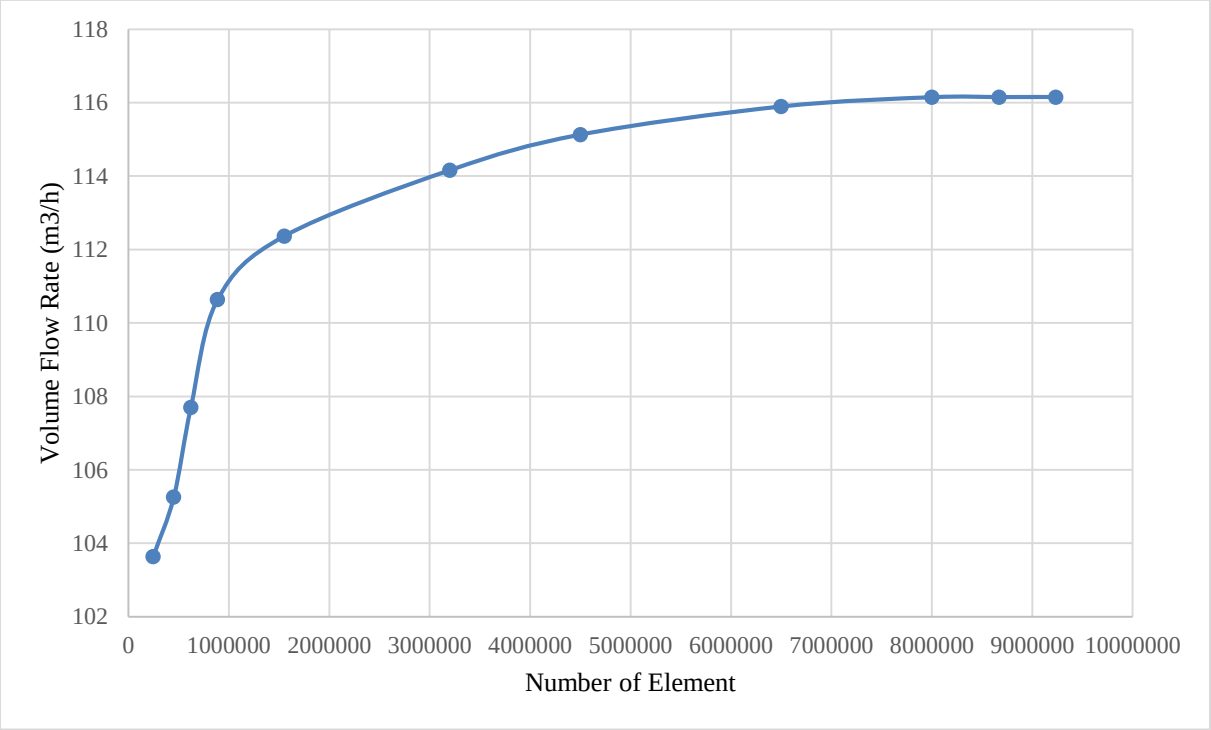

Figure 5. Mesh independence study curve

In order to better interpret the characteristics of this behaviour, velocity vector analysis was performed. Accordingly, when the valve is in the fully open position, the resistance of the valve and its body against flow can be characterized more clearly. Velocity vector analysis of the system in Fig. 6 is given for a better understanding of the subject.

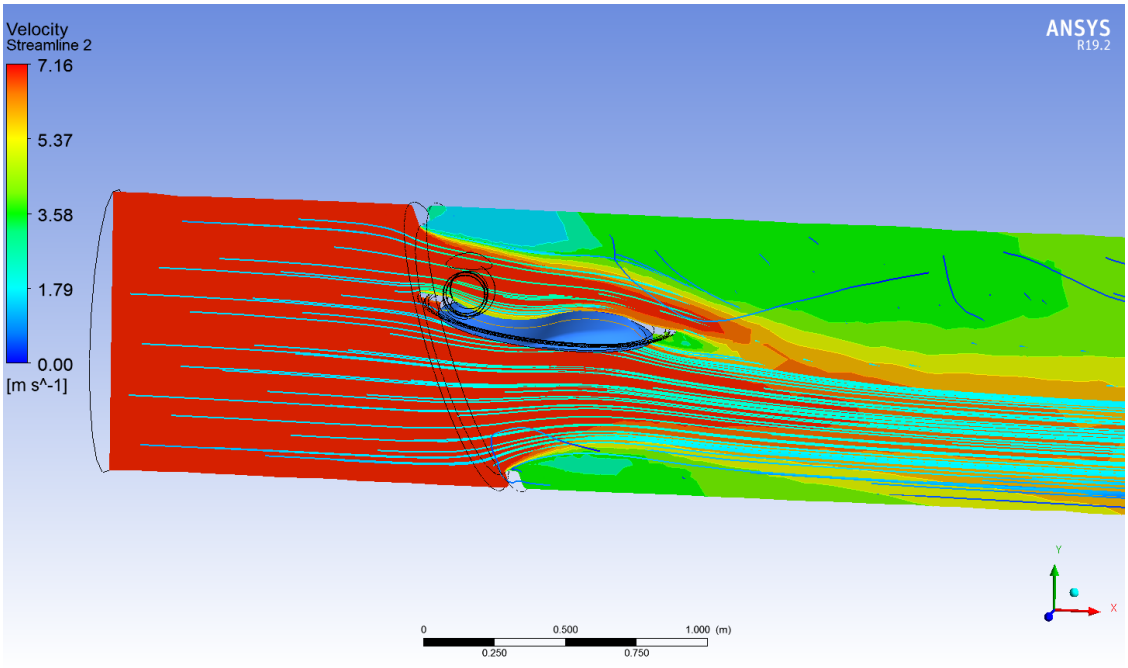

Figure 6. Flow velocity vector analysis of the developed design

The other parameter that will support the velocity vector analysis of this system will be its characteristic behaviour under 16 bar pressure. The pressure distribution of the system is shown in Fig. 7.

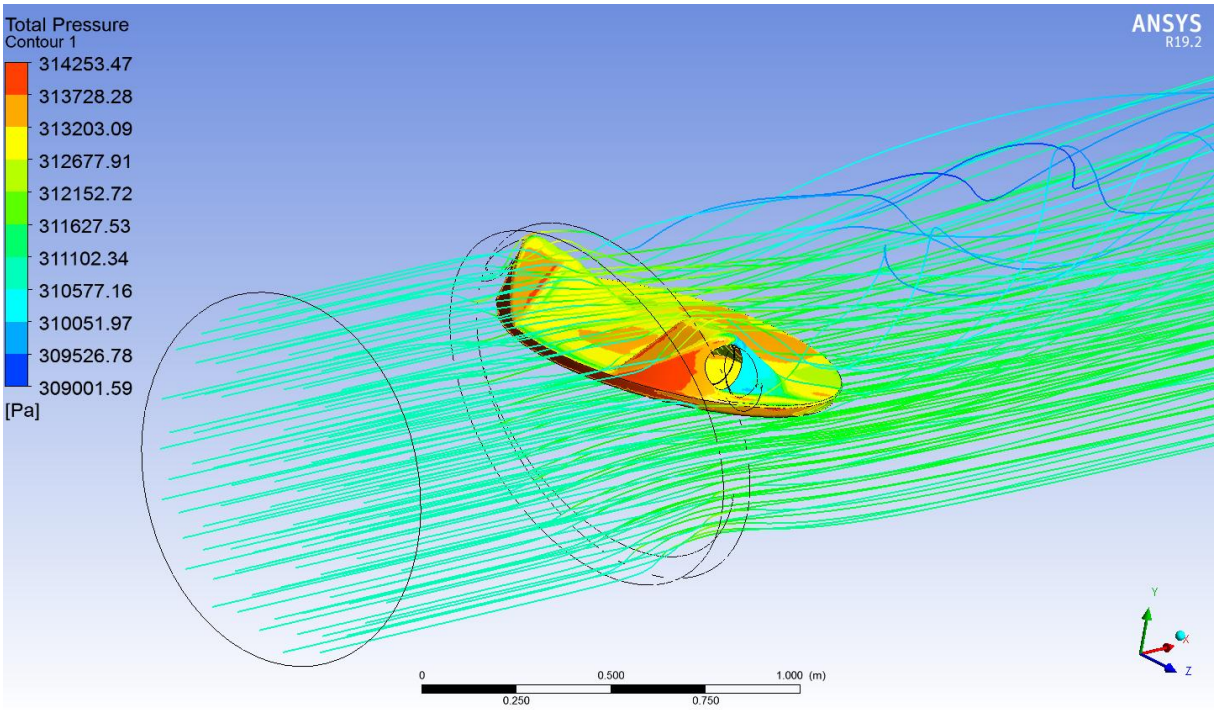

Figure 7. Total pressure distribution on the surface

When the flow occurs at a certain speed and pressure, the distribution analysis of the flow filaments of the system is performed and the total strength is analysed. Fig. 8 shows the flow filament distribution analysis of the system under 16 bar pressure at 4m/s vector speed.

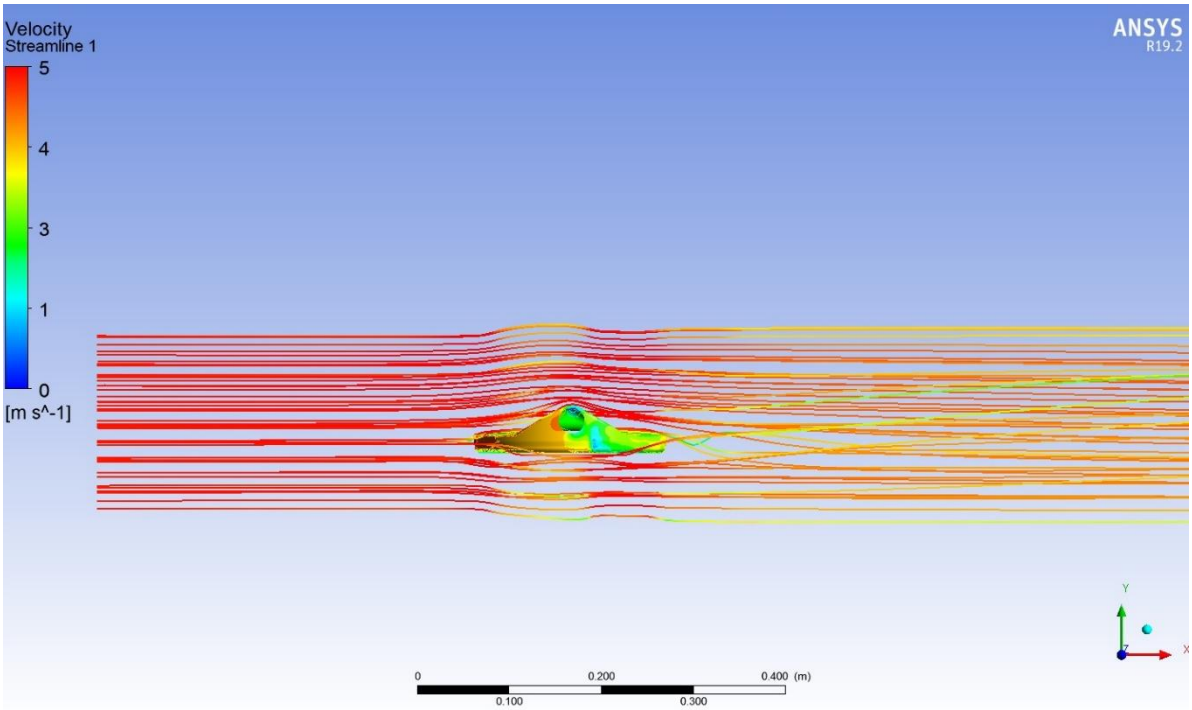

Figure 8. Flow filament distribution analysis

After all flow and pressure analyses were carried out, hydrodynamic forces on the valve were analysed. Fig. 9 shows the CFD analysis visual of the hydrodynamic forces on the ring.

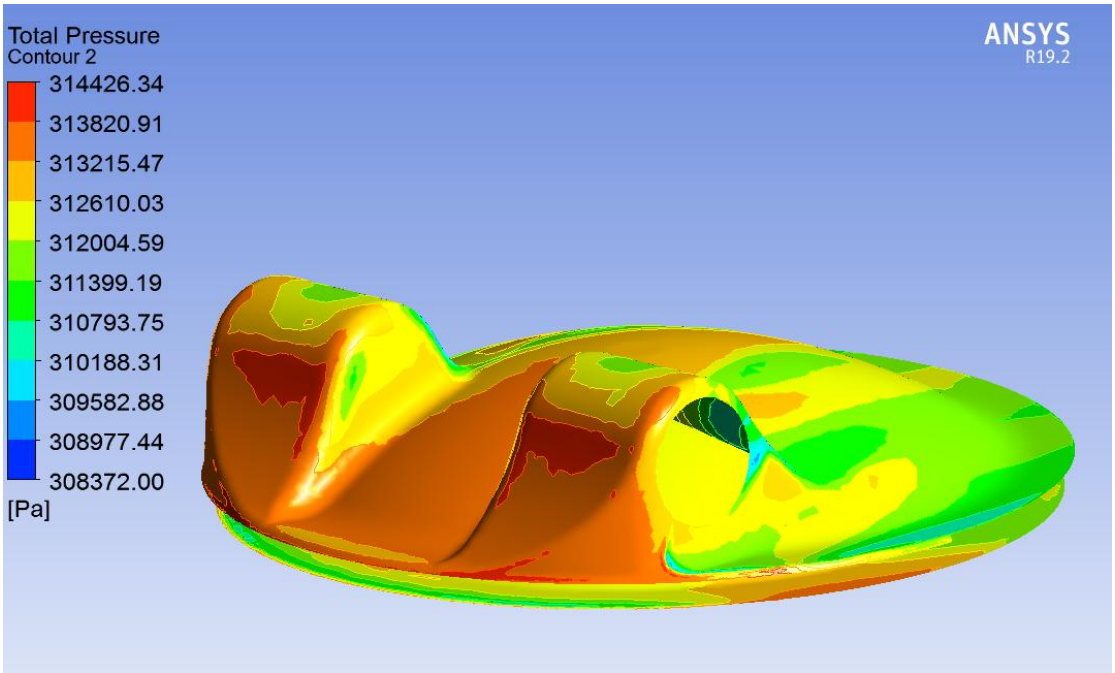

Figure 9. Total pressure distribution analysis applied on the surface on the ring

2.5. Design verification, validation and prototype production

The casting model and core box of the valve, whose hydrodynamic properties were analysed and designed, were produced on Computer Aided Manufacturing (CAM) software and Computerized Numerical Control (CNC) benches. Fig. 10 shows the wooden pattern production of the ring.

Figure 10. Model production of the ring

Details of the pattern dimensions are given in mm in Fig. 11. to explain along with its dimensions.

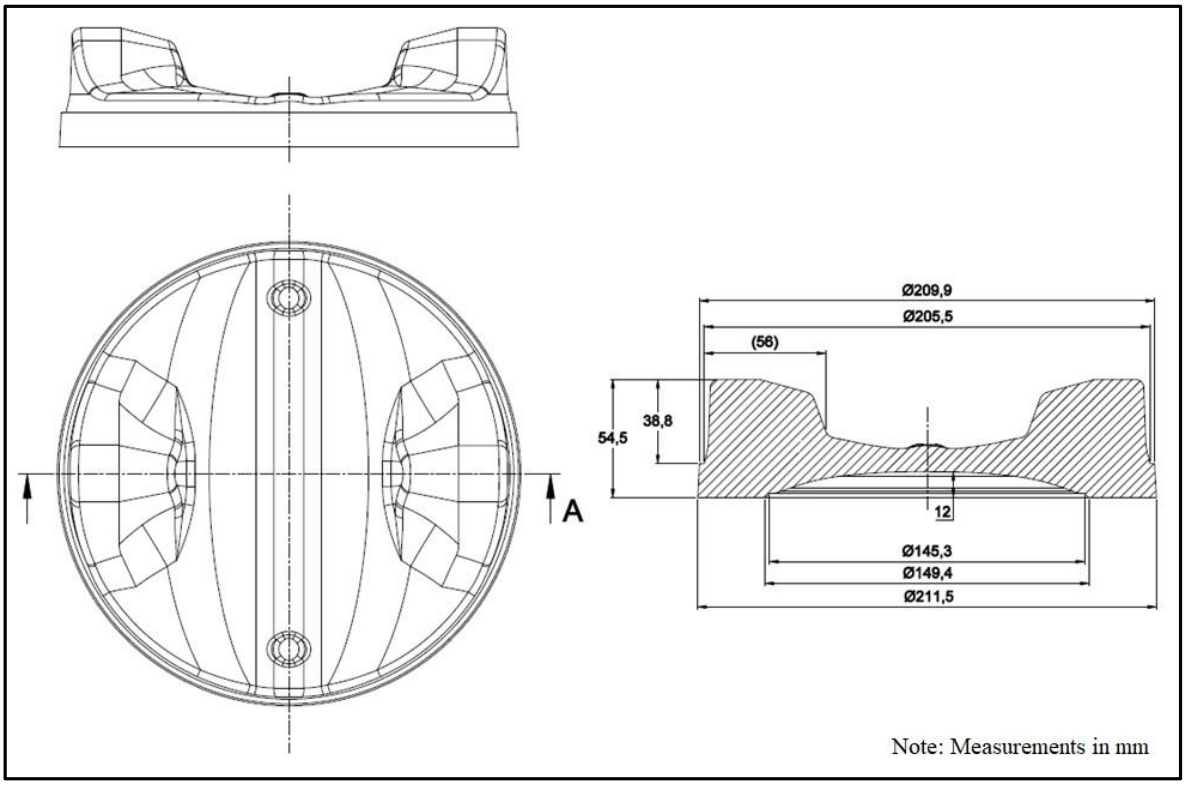

Figure 11. Model explanation along with its dimensions

The model design of the body on which the ring would be mounted, where the designed mechanical strength analyses were verified by simulation, is shown in Fig. 12.

Figure 12. The finish pattern of the ring for the body assembling

The dimension control of the cast body was carried out with the Faro Arm Quantum device and the report of the measurements was obtained by Faro CAM2 software. Fig. 13 shows the report of the precise measurements of the body casting.

Figure 13. Dimension CMM report

Simulated pressure tests of the produced body and the mounted ring were carried out in accordance with EN 1074. Pressure tests were evaluated according to whether the valve was leaking or damaged under 24 bar pressure for the body. The design in which the pressure test was carried out is shown in Fig. 14.

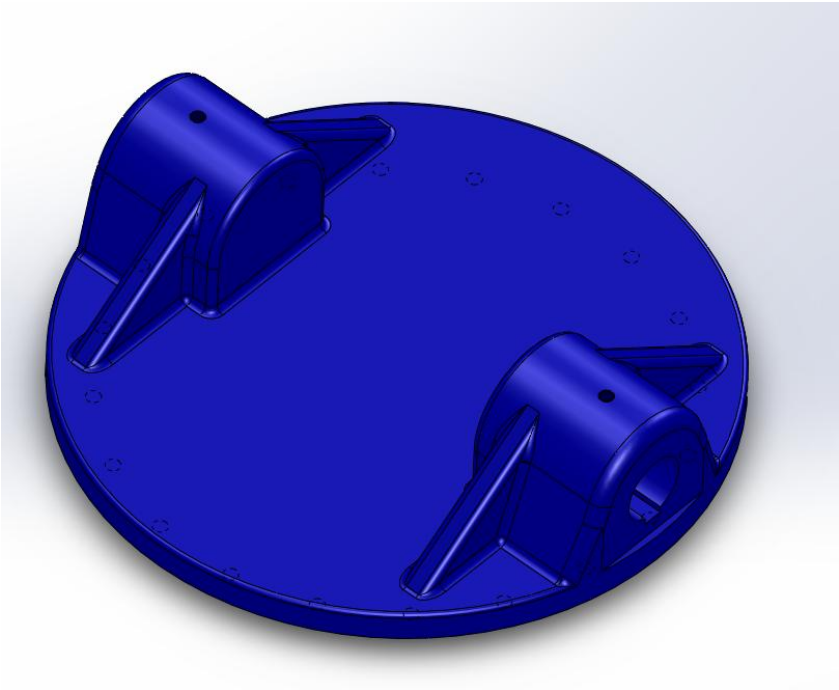

Figure 14. The ring final design for the pressure test

According to the TS EN 1267 flow resistance test standard, the valve was modeled in the Solidworks drawing program in a fully open position. The modeling performed is shown in Fig. 15.

Figure 15. Three-dimensional valve test verification model

Defining fluid inlet and outlet boundary conditions was of critical importance in this modelling. According to the standard the inlet boundary conditions were defined at a distance of 2xDN from the valve, and outlet boundary conditions were defined at a distance of 10xDN. Fig. 16 shows the fluid direction design for CFD.

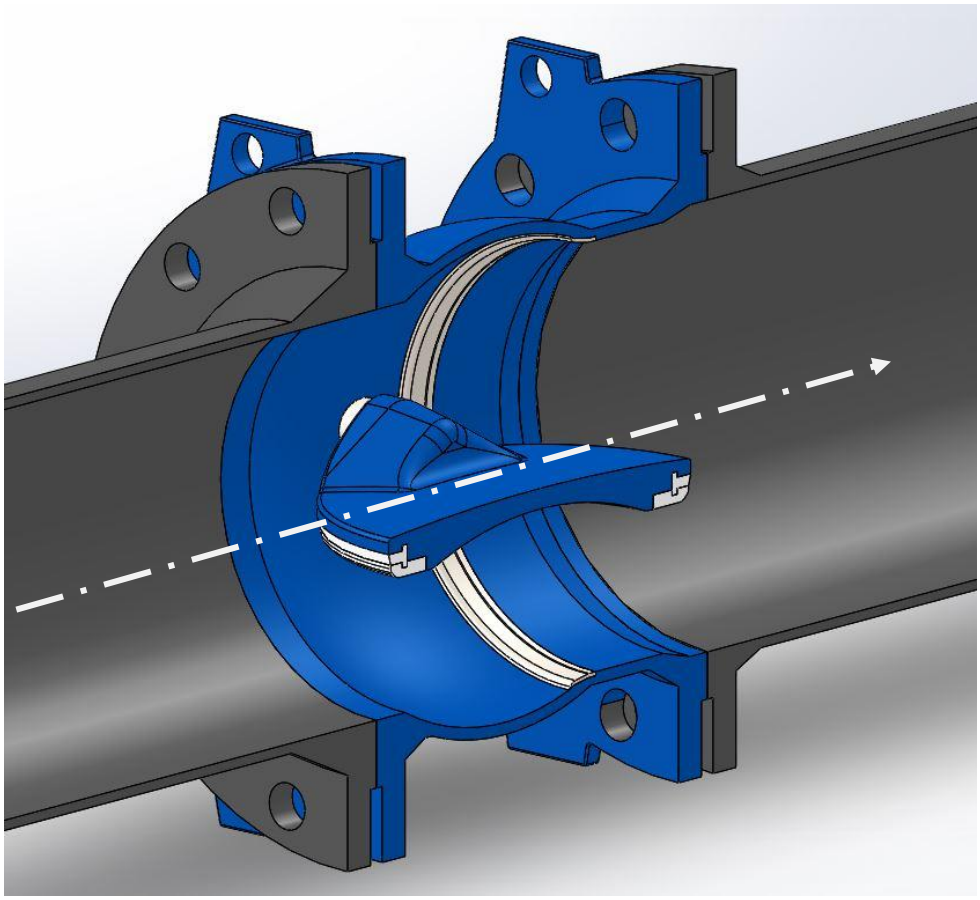

Figure 16. Determining fluid directions for CFD

According to the conservation principle, fluid movement is by trying to define the flow structure in detail at every point of the field or by using a finite by working with the region and establishing the balance between the incoming flow and the outgoing flow. If the continuity equation is applied to circular cross-section pipe flows, the continuity equation will be cylindrical due to the geometric shape of the flow field and the control volume selected accordingly. It should be applied in coordinates (r,θ,z). Incompressible flows in cylindrical coordinate system and the continuity equation for is as follows

$$\frac{1}{r}\frac{\partial(rV_r)}{\partial r}+\frac{1}{r}\frac{\partial(rV_\theta)}{\partial \theta}+\frac{1}{r}\frac{\partial(rV_z)}{\partial z}=0 \qquad (2)$$

Here, r, θ and z are the radial (radius), tangential (circumferential) and axial directions, respectively, and vr, vθ and vz refers to the flow velocities in radial, tangential and axial directions, respectively.

Flow capacity measurements of the body and ring, which did not detect any problems in the simulation studies and were produced accordingly, were made in the Kv test device. Fig. 17 shows the prototype Kv test setup.

Figure 17. Kv test setup for the designed prototype

3. Results and Discussion

Product and experimental designs were carried out with a line pressure of 16 bar, and no plastic deformation or leakage was observed in the product under 16 bar line pressure.

Simulation studies were carried out so that the fluid coefficient Kv was 3009.9 m^3/hour when the valve was in the fully open position under 16 bar internal pressure and 4 m/s fluid speed. The values obtained as a result of the tests and flow analysis were measured as 2985 m^3/hour. This measurement corresponds to a margin of error of 5% when compared to the design, and in EN 1074 standards this deviation is expected to be below 10%. For this reason, it was determined that the flow analysis and physical test results were compatible with each other and no nonconformities were encountered. The results are included in the physical test report given in Table 1.

Table 1. Physical test report

COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS REPORT					
VALVE TYPE : DOUBLE ECCENTRIC BUTTERFLY VALVE / ***Dikkan Ultra Series***					
DN : 200 (200) / (Default fluid velocity : 4 m/s)					
PN : 16					
OPENED POSITION OF OBTURATOR (%) : 100					
Inlet Pressure (bar)	Outlet Pressure (bar)	Velocity from CFD Result (m/s)	Fluid Flow Rate (m^3/h)	Differantial Pressure (ΔP) (bar)	**Kv** (m^3/h)
15,99999	15,97740	4,096	452,4	0,02259	**3009,9**

Resistance to 1.5 x 16 bar = 24 bar body internal pressure and 1.1 x 16 bar = 18 bar leakage tests of product components specified in TS EN 12266 standard have been successfully carried out. The values in most valves might vary due to losses caused by friction resulting from the actual length of the flow path, sudden changes in the flow direction, and surface roughness, but when the prototype manufacturing real test results and simulation results were compared, no difference was detected in

the Kv values of the product, computer-aided design and prototype production, so the data overlapped almost exactly.

Fig. 18 shows images of the old and new body designs. The curved body, where flow properties were improved, can be observed more clearly in this picture.

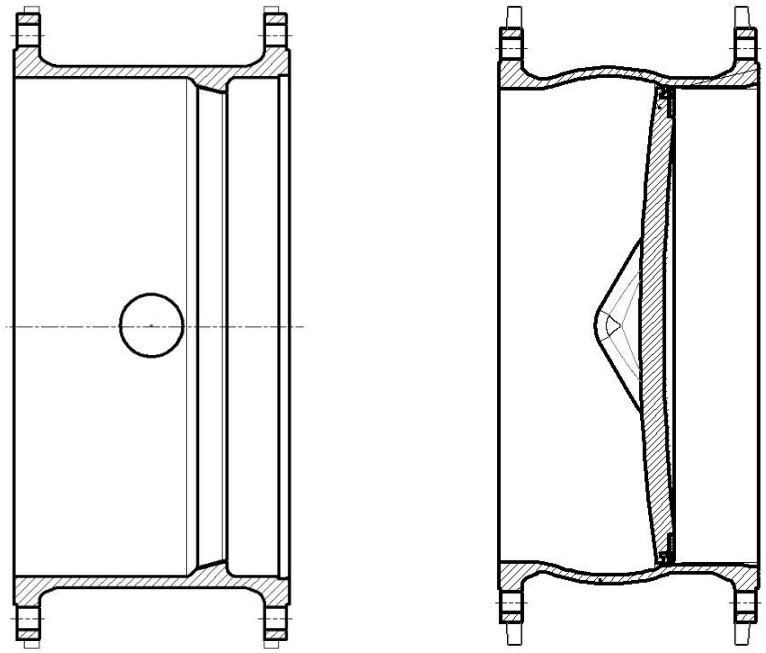

Figure 18. Images of old (left) and new (right) body designs

Fig. 19 shows the visual of the old and new disc designs mounted on the valve. The green colour represents the old design, and the red colour represents the new design. The gain in surface area, which provides 20% more and homogeneous flow, can be noticed in this picture.

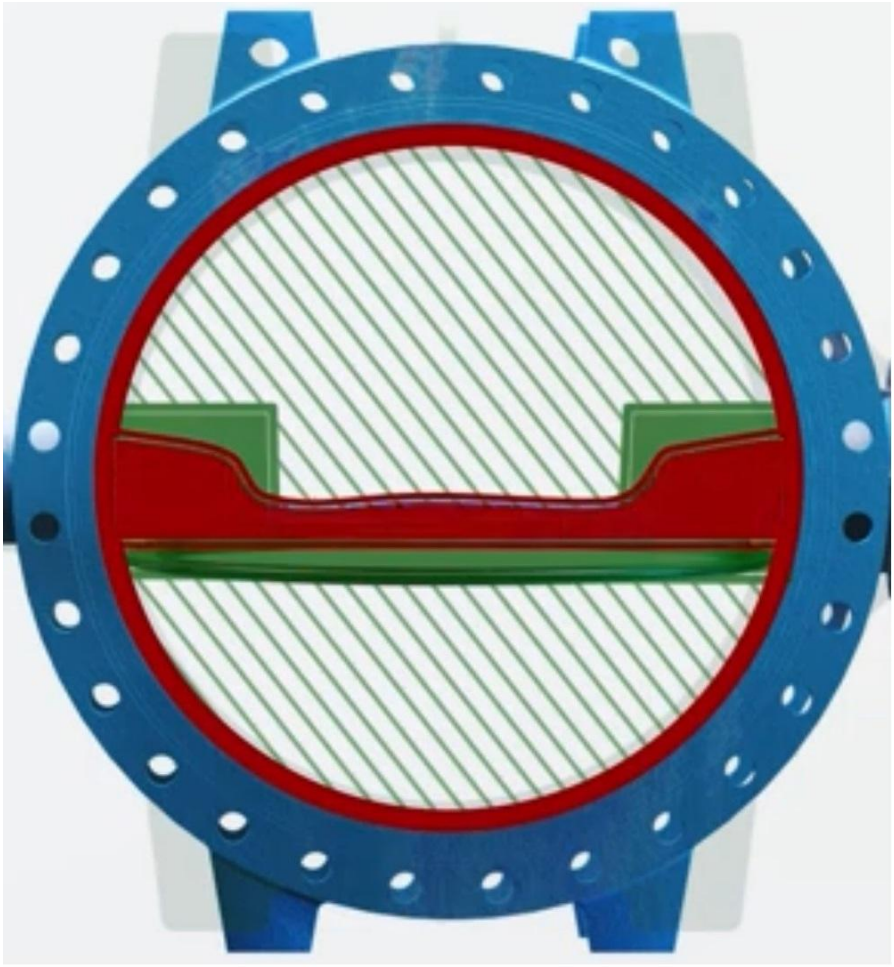

Figure 19. Superimposed image of old and new disc designs

In the flow tests performed according to the minimum 240 N/mm^2 yield strength in the body design, no negative effects were detected under 16 bar and no plastic deformation occurred in the product under 24 bar pressure.

Resistance to 1.5 x 16 bar = 24 bar body internal pressure and 1.1 x 16 bar = 18 bar sealing tests of product components specified in TS EN 12266 standard have been successfully carried out. In most valves, these values vary due to losses caused by friction resulting from the actual length of the flow path, sudden changes in the flow direction, obstacles in the flow direction and surface roughness, but when the prototype manufacturing test results and simulation results are compared, no difference was detected in the Kv values of the product and computer-aided design and prototype production. The data overlapped almost exactly.

In the tests of the ring material, no problems were detected under stresses exceeding 1.1 times, no deformation was observed under loads twice the maximum pressure, and the product successfully met the requirements of the EN 1074 standard.

With the Solidworks sustainability report, a carbon footprint of 140 kg CO_2 per product was achieved, and 26% improvement in existing products. The design and prototype manufacturing of the product, which would achieve 32% energy saving with a total energy consumption of 1400 MJ/product with material, production and product life, has been carried out (Fig. 20). This chart was obtained by making a systematic comparison of 24 national and international products in the sector. Finally, national and

international patent applications have been completed for the unique curved body and gradual shaft designs obtained during the development phase of the product.

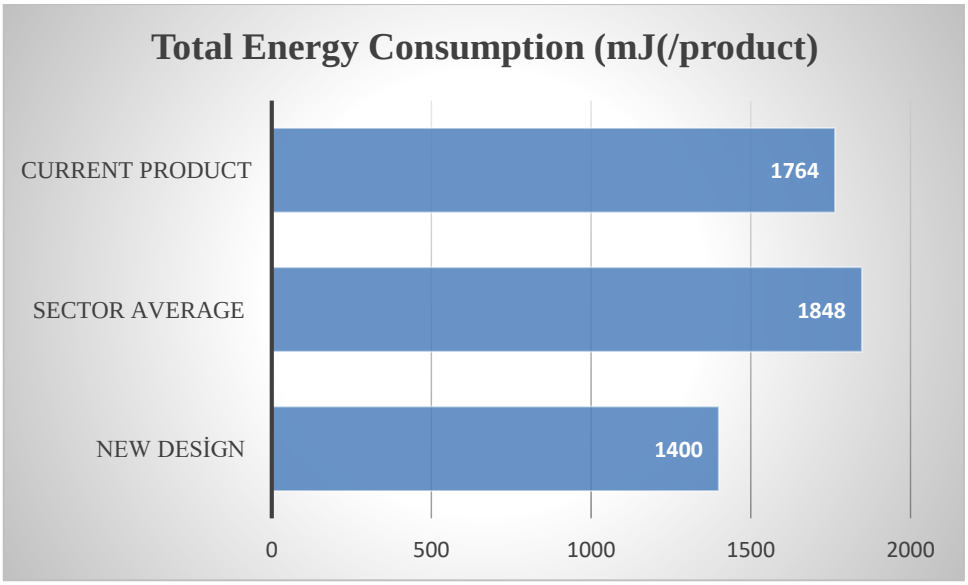

Figure 20. Total energy consumption graph

4. Conclusion

Efficient use of water resources has become inevitable within the scope of combating the climate crisis. Efforts continue to reduce the carbon footprint, which is one of the main reasons for the climate crisis and a measure of global warming. As a result of this study, energy losses were reduced by 32% and carbon footprint was reduced by 26% with improvements in flow coefficients in the butterfly valve product designed. The 95% overlap between simulation-supported tests and real test data in body and ring designs has once again demonstrated the importance of simulation-supported designs. As a result of the studies carried out in the article, national and international patent applications were made for the unique curved body and stepped ring structure. The first patent in the valve industry was published in 1839, and patents for almost all valve components were obtained in the mid-1900s. Therefore, all national and international patents were scanned, and it was determined that no patents were received regarding the developed curved body and gradual ring design. This result made the study more original. Finalization of the commercialization of the studies carried out in the article, a completely domestic and national product that is long-lasting, highly energy efficient, and aims to protect environmental and human health values has been introduced to the valve industry.

List of Symbols

CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
CAD	Computer Aided Manufacturing
CNC	Computerized Numerical Control

Declarations and Ethical Standards

The author declared no potential conflicts of interest with respect to the study, authorship, and/or publication of this article. The author of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Author Contribution

The all stages including computer aided design, simulations, prototype production and validation tests of this study were carried out by Erhan Özkan.

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alpha
Journal of Engineering and Applied Sciences
(AJEAS)
e-ISSN: 3023-6002

Alfa Mühendislik ve Uygulamalı Bilimler Dergisi
(2024) 3/1: 35 – 50

Araştırma Makalesi

DOI: 10.70988/ajeas.1628985

Gönderi (Received): 29/01/2024

Kabul (Accepted): 22/03/2025

Yayın (Published): 30/04/2025

Dağıtık Siber Saldırıların İnternet Hizmetlerinin Kullanılabilirliği Üzerindeki Etkisi: DDoSphere ile Deneysel Bir Analiz

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Özet

Bu araştırma, farklı coğrafi konumlardan kaynaklanan yoğun trafiği kullanarak sistemleri çökerten siber saldırılar olan DDoS saldırılarının, ağ performansını nasıl etkilediğini incelemeyi amaçlamıştır. Volumetrik, protokol ve uygulama katmanındaki DDoS saldırılarının, ağ üzerindeki etkileri simülasyonlarla incelenmiş ve bu saldırıların sistemlerin işlem gücünü ve bant genişliğini nasıl tükettiği detaylı olarak analiz edilmiştir. Özellikle çoklu kaynaklı saldırıların, tespit ve savunma sistemlerini zorlaması üzerine odaklanan bu çalışma, Ddosphere simülasyon aracıyla desteklenmiştir. Elde edilen sonuçlar, ağ yöneticileri ve siber güvenlik uzmanlarına, ağ performansını artırmak ve DDoS saldırılarına karşı daha etkili savunma stratejileri geliştirmek için değerli bilgiler sunmaktadır. Bu çalışma, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu'nun desteklediği "DDOS Tabanlı Siber Saldırı Test Modülü" projesi kapsamında Virgosol tarafından yürütülmüştür.

Anahtar kelimeler: *DDoS saldırıları, Ağ performansı, Siber güvenlik, Ddosphere, Çoklu konumlu saldırılar, Simülasyon tabanlı analiz, Savunma stratejileri*

The Impact of Distributed Cyberattacks on the Availability of Internet Services: An Empirical Analysis with DDoSphere

Abstract

This research aims to examine how DDoS attacks, which are cyberattacks that use heavy traffic from different geographical locations to disrupt systems, affect network performance. The impact of DDoS attacks at the volumetric, protocol, and application layers on networks was analyzed through simulations, and the way these attacks consume system processing power and bandwidth thoroughly studied. This study specifically focuses on the challenges posed by multi-sourced attacks to detection and defense mechanisms, and is supported by the Ddosphere simulation tool. The findings provide valuable insights for network administrators and cybersecurity experts to enhance network performance and to develop more effective defense strategies against DDoS attacks. This study was conducted by Virgosol within the scope of the "DDoS-Based Cyberattack Test Module" project, and it was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK)

Keywords: *DDoS attacks, Network performance, CyberSecurity, Ddosphere, Multi-location attacks, Simulation-based analysis, Defense strategies*

Citation: D. Öztürk, A. Aktolun, M. Emektar, F.M. Harmancı, "Dağıtık Siber Saldırıların İnternet Hizmetlerinin Kullanılabilirliği Üzerindeki Etkisi: DDoSphere ile Deneysel Bir Analiz", AJEAS. (2025) 3(1): 35-50. http://dx.doi.org/10.70988/ajeas.1628985

1. Giriş *(Introduction)*

İnternet, dünya çapında yüz milyonlarca bilgisayarı birbirine bağlayan ve farklı donanım ve yazılım platformlarında çalışan devasa bir ağdır. İnternet, hem kişisel hem de kurumsal ihtiyaçları karşılayarak önemli hizmetler sunar. Ancak, bu ağ üzerinden sağlanan bağlantılar, kötü niyetli kullanıcıların kaynakları kötüye kullanmasına ve belirli sitelere yönelik hizmet reddi (DoS) saldırıları gerçekleştirmesine olanak tanır.

Hizmet reddi saldırısı, kötü niyetli bir kullanıcının internetin bağlantı olanaklarını kullanarak bir sitenin hizmetlerini engellemeye çalıştığı bir durumdur. Genellikle bu, hedef siteye aşırı miktarda istek gönderilerek gerçekleştirilir [1]. Bu tür saldırılar, tek bir kaynaktan gelebileceği gibi, birçok bilgisayarın koordine bir şekilde hedefe istek yağmuru göndermesiyle de yapılabilir. Bu ikinci tür saldırıya, dağıtık hizmet reddi (DDoS) saldırısı denir.

İnternet ortamı geniş bilgi ve araçlara ev sahipliği yapmaktadır, kötü niyetli saldırılar düzenlemeyi otomatikleştiren gelişmiş saldırı araçlarını da barındırır ve ayrıntılı kullanım talimatları sayesinde, amatörler bile bu araçları kolaylıkla ve etkili bir şekilde kullanabilir [1].

Hizmet reddi saldırıları her yıl önemli finansal zararlara neden olur ve bu nedenle, bu tür saldırıları hızla tespit edip yanıt verecek tekniklerin geliştirilmesi büyük önem taşır. Bu durumun çarpıcı bir örneği, ABD merkezli bulut tabanlı bir Git deposu barındırma hizmeti sunan GitHub'ın tarihin en büyük DDoS saldırılarından birine maruz kalmasıyla yaşandı. Bu saldırıda, bilinmeyen hackerlar platforma 1,35 Tbps'lik devasa bir trafik yükleyerek GitHub'ı çevrimdışı bırakmaya çalıştı. Sonuç olarak, ABD'nin geniş bir bölgesindeki önemli web siteleri saatlerce hizmet dışı kaldı [2].

Günümüzde DDoS saldırıları hem yöntem hem de şiddet bakımından yeni boyutlara ulaşmış durumda ve mevcut eğilimler, benzer saldırıların gelecekte de gerçekleşebileceğini göstermektedir. Siber güvenlik, kuruluşların siber savaşta galip gelebilmesi için kritik bir rol oynar. İşletmeler, siber güvenlik önlemlerini diğer operasyonel süreçlerle aynı öncelikte değerlendirmediğinde, yalnızca bir sonraki DDoS saldırısının hedefi olma riskiyle kalmazlar; aynı zamanda büyük çapta itibar kaybı ve mali zararlara da maruz kalabilirler.

Hizmet reddi saldırıları, kaynaklarına göre iki ana gruba ayrılabilir: bunlar tek kaynaklı ve çok kaynaklı saldırılardır. Tek kaynaklı DoS saldırıları, gerçekten de tek bir cihaz veya IP adresinden gelen zararlı trafikle sistemleri işlevsiz hale getirmeye çalışır. Bu tür saldırılarda, saldırgan tüm trafiği belirli bir noktadan gönderir, bu da saldırının kaynağını tespit etmeyi ve engellemeyi nispeten daha kolay hale getirebilir.

Çok kaynaklı saldırılar ise genellikle farklı coğrafi bölgelerden gelen trafiği içerir. Bu tür saldırılar, saldırganların farklı fiziksel lokasyonlardan aynı anda saldırı başlatmasıyla gerçekleştirilir. Bu, saldırının tespit edilmesini ve önlenmesini daha da zorlaştırır, çünkü saldırı trafiği farklı ülkelerden veya bölgelerden gelebilir. Bu da saldırıya karşı alınacak önlemleri karmaşık hale getirir.

Bu çalışmanın amacı, farklı coğrafi konumlardan gelen dağıtılmış hizmet reddi (DDoS) saldırılarının ağ performansı üzerindeki etkilerini incelemektir. Çalışmada, volumetrik saldırılar (örneğin, UDP Flood), protokol saldırıları (örneğin, SYN Flood) ve uygulama katmanı saldırıları (örneğin, HTTP Flood) gibi farklı DDoS saldırı türlerinin ağ üzerindeki etkileri analiz edilecektir. Bu saldırıların, gecikme süresi, paket kaybı ve bant genişliği kullanımı gibi kritik ağ performans metrikleri üzerindeki etkileri değerlendirilecektir. Ayrıca, Ddosphere simülasyon aracı kullanılarak tek lokasyondan ve çoklu lokasyonlardan gerçekleştirilen saldırıların karşılaştırmalı analizi yapılacak, çoklu kaynaklı

saldırıların tespit ve savunma sistemleri üzerindeki etkileri detaylı olarak incelenecektir. Çalışmanın amacı, çoklu lokasyonlardan gelen dağıtılmış hizmet reddi (DDoS) saldırılarının ağ performansı üzerindeki etkilerini incelemektir.

Çalışmamızda öncelikle, DDoS saldırılarının temel prensiplerini ve türlerini ele alacağız. Ardından tek lokasyondan ve çoklu lokasyonlardan gelen saldırıların özelliklerini ve bu saldırıların ağ üzerindeki spesifik etkilerini analiz edeceğiz. Bu bağlamda, Ddosphere ürününden faydalanarak tek lokasyondan ve çoklu lokasyonlardan gerçekleştirilen saldırıların ağ performansı üzerindeki farklarını simüle edecek ve bu simülasyonlar üzerinden performans değerlendirmeleri yapacağız. Ddosphere, saldırıları canlı olarak izlememizi, hedef sistemin performansını analiz etmemizi ve bu analizleri detaylı raporlarla sunmamızı sağlayan gelişmiş bir simülasyon aracıdır.

Bu çalışma, siber güvenlik uzmanları, ağ yöneticileri ve işletmeler için tek lokasyon ve çoklu lokasyonlardan gelen DDoS saldırılarına karşı daha bilinçli ve hazırlıklı olmalarına yardımcı olmayı amaçlamaktadır. Ddosphere kullanarak gerçekleştirilen simülasyonlar, farklı saldırı senaryolarının ağ performansını nasıl etkilediğini canlı olarak gözlemleme ve analiz etme imkânı sunacak, bu da savunma stratejilerinin etkinliğini artırmak için kritik veriler sağlayacaktır.

Sonuç olarak, çalışmamız, ağ performansını optimize etmek ve DDoS saldırılarına karşı etkili savunma mekanizmaları geliştirmek için gerekli olan bilgileri ve analizleri sunarak, siber güvenlik alanında önemli bir katkı sağlamayı hedeflemektedir.

2. DDoS Saldırısı *(DDoS Attack)*

Bu bölümde, DDoS saldırılarının türleri, gerçekleştirmek için kullanılan yöntemler, tarihsel gelişimi ve ağ performansı üzerindeki etkileri incelenecektir.

2.1. DDoS Saldırılarının Tarihsel Gelişimi *(The Historical Development of DDoS Attacks)*

Dağıtılmış Hizmet Reddi (DDoS) saldırıları, internetin yaygınlaşmasıyla birlikte evrim geçirmiş ve giderek daha karmaşık ve etkili hale gelmiştir. İlk basit saldırılardan günümüzün büyük ölçekli botnet destekli saldırılarına kadar DDoS'un gelişimi aşağıda detaylandırılmaktadır (Tablo 1).

2.1.1. 1990'lar: DDoS kavramının ortaya çıkışı *(The 1990s: The emergence of the DDoS concept)*

DDoS saldırılarının kökeni 1990'lı yıllara dayanmaktadır. İlk örneklerden biri, 1999 yılında "Trinoo" adlı bir saldırı aracıyla gerçekleştirilen saldırıdır [3]. Trinoo, yüzlerce bilgisayardan gelen yoğun trafikle hedef sunucuları devre dışı bırakmayı amaçlayan bir saldırı türüydü. Benzer şekilde, TFN (Tribe Flood Network) ve Stacheldraht gibi saldırı araçları, DDoS saldırılarının ilk nesil araçları arasında yer aldı [4].

2.1.2. 2000'ler: İlk büyük ölçekli DDoS saldırıları *(The 2000s: The first large-scale DDoS attacks)*

2000'li yılların başında, DDoS saldırıları geniş çapta zarar vermeye başladı. Özellikle Şubat 2000'de, bir genç hacker olan Mafiaboy, Yahoo, CNN, Amazon ve eBay gibi büyük sitelere koordineli DDoS saldırıları düzenleyerek hizmetlerini kesintiye uğrattı [5]. Bu saldırılar, DDoS'un internet altyapısını tehdit edebileceğini açıkça gösterdi.

2003 yılında, SQL Slammer ve Blaster solucanları, sistem açıklarını kullanarak yaygın DDoS saldırıları gerçekleştirdi [6]. Bu saldırılar, bir sistemdeki zafiyetin kullanılarak dünya genelindeki birçok sunucunun devre dışı bırakılabileceğini kanıtladı (Tablo 1).

Tablo 1. Büyük ölçekli DDoS saldırıları ***(Large-Scale DDoS Attacks)***

Yıl	Saldırı	Öne Çıkan Noktalar
1999	Trinoo, TFN, Stacheldraht	İlk DDoS saldırıları [3]
2000	Mafiaboy Saldırıları	Yahoo, Amazon ve CNN gibi büyük siteler hedef alındı [5]
2003	SQL Slammer	Worm tabanlı saldırılar başladı [6]
2013	Spamhaus DNS Amplifikasyon	300 Gbps saldırı kapasitesine ulaşıldı [7]
2016	Mirai Botnet	IoT cihazları hedef alındı, 600 Gbps saldırılar [8]
2018	GitHub Saldırısı	1.35 Tbps ile en büyük saldırılardan biri gerçekleşti [9]
2020	AWS 2.3 Tbps Saldırısı	En büyük volumetrik saldırı [10]
2022	Cloudflare & Azure Saldırıları	26 milyon RPS'ye ulaşan HTTP Flood saldırıları [11]
2023+	AI Destekli Botnetler	Yapay zeka kullanılarak daha sofistike saldırılar düzenlenmekte [12]

2.1.3. 2010'lar: Botnet destekli büyük ölçekli saldırılar *(The 2010s: Large-scale botnet-driven attacks)*

2010'lu yıllar, botnetlerin yükselişi ile DDoS saldırılarında büyük bir değişime sahne oldu.

- 2012 - 2014 Cloudflare ve Spamhaus Saldırıları: 2013 yılında, Spamhaus adlı bir anti-spam organizasyonu, 300 Gbps'yi aşan bir DDoS saldırısına maruz kaldı. Bu saldırı, dönemin en büyük DNS Amplifikasyon saldırılarından biri olarak kaydedildi [7].
- 2016 Mirai Botnet: IoT (Nesnelerin İnterneti) cihazlarını ele geçirerek 600 Gbps büyüklüğünde saldırılar gerçekleştiren Mirai botneti, Dyn DNS, OVH ve KrebsOnSecurity gibi büyük hedeflere saldırarak internetin büyük bir bölümünü etkiledi [8].
- 2018 GitHub Saldırısı: GitHub, 1.35 Tbps büyüklüğünde bir DDoS saldırısına maruz kalarak en büyük saldırılardan birine tanık oldu [9].

2.1.4. 2020 ve Sonrası: Rekor kıran DDoS saldırıları *(2020 and Beyond: Record-breaking DDoS attacks)*

Son yıllarda DDoS saldırıları daha büyük ve sofistike hale gelmiştir.

- 2020 AWS'ye Yönelik 2.3 Tbps'lik Saldırı: Amazon Web Services (AWS), 2.3 Tbps hızında bir saldırıya maruz kalarak tarihin en büyük DDoS saldırılarından birini yaşadı [10].
- 2022 Cloudflare ve Microsoft Azure'a Yönelik Saldırılar: Cloudflare ve Microsoft Azure gibi büyük bulut sağlayıcıları, saniyede 26 milyon istek seviyesine ulaşan HTTP Flood saldırılarıyla hedef alındı [11].
- 2023 - 2024 Yapay Zeka Destekli Saldırılar: Son dönemde, saldırganlar yapay zeka (AI) destekli botnetler ile daha karmaşık DDoS saldırıları düzenlemektedir [12]. Ayrıca, Web3 ve blok zinciri altyapılarına yönelik DDoS saldırıları da artış göstermektedir [13].

DDoS saldırıları, basit tek noktadan yapılan saldırılardan gelişmiş botnet ve yapay zeka destekli koordineli saldırılara evrilmiştir. Siber güvenlik önlemleri gelişse de, saldırganlar da yeni teknikler geliştirerek savunma sistemlerini aşmaya çalışmaktadır. Bu nedenle, gelecekte otomatik tespit sistemleri, yapay zeka destekli güvenlik çözümleri ve proaktif savunma mekanizmaları daha kritik hale gelecektir.

2.2. DDoS Saldırı Türleri ve Yöntemleri *(Types and Methods of DDoS Attacks)*

DDoS saldırıları, farklı teknikler kullanarak çeşitli katmanlarda gerçekleştirilir ve genel olarak üç ana türde incelenir: Volumetrik saldırılar, protokol saldırıları ve uygulama katmanı saldırıları.

2.2.1. Volumetrik saldırılar *(Volumetric attacks)*

Volumetrik saldırılar, hedefin bant genişliğini tüketerek ağ trafiğini tıkayan saldırılardır. Bu saldırılar, büyük miktarda veri trafiği göndererek hedefin ağ altyapısını boğar. Volümetrik saldırılardan biri olan UDP Flood saldırısında, UDP protokolü kullanılarak rastgele portlara büyük miktarda veri paketi gönderilir ve hedef sistem bu paketlere yanıt vermek zorunda kalarak kaynaklarını tüketir [14]. ICMP Flood saldırısında ise hedefe büyük miktarda ICMP ECHO REQUEST paketleri gönderilir. Hedef, bu paketlere yanıt vermek zorunda kalarak bant genişliğini ve işlem kaynaklarını tüketir [15].

2.2.2. Protokol saldırıları *(Protocol attacks)*

Protokol saldırıları, ağ katmanındaki zafiyetleri hedef alır ve hedefin kaynaklarını tüketerek hizmetlerin aksamasına yol açar. Protokol Saldırılarından SYN Flood saldırısında; TCP bağlantı kurulumu sırasında SYN paketleri gönderilir, ancak bağlantı tamamlanmaz. Bu durum, hedef sistemde yarım kalmış bağlantıların birikmesine neden olur ve sistemin kaynaklarını tüketir [16]. Smurf Attackta ise saldırgan, hedefin IP adresini sahte bir şekilde kaynak IP olarak göstererek ICMP, ECHO, REQUEST paketlerini geniş bir ağa gönderir. Ağdaki cihazlar, hedefe yanıt gönderir ve bu da hedefin bant genişliğini aşırı yükler [17].

2.2.3. Uygulama katmanı saldırıları *(Application layer attacks)*

Uygulama katmanı saldırıları, hedefin uygulama katmanında bulunan zafiyetleri kullanarak hizmetleri aksatmayı amaçlar. Bu saldırılar, genellikle daha az bant genişliği kullanarak yüksek etki yaratır. Uygulama Katmanı saldırılarından HTTP Flood saldırısında HTTP protokolü kullanılarak hedef web sunucusuna büyük miktarda istek gönderilir. Bu, sunucunun kaynaklarını tüketir ve hizmet vermesini engeller [18]. Slowloris saldırısında Saldırgan, hedef web sunucusuna çok sayıda yarım kalmış HTTP bağlantısı açar. Bu, sunucunun kaynaklarını tüketir ve yeni bağlantıları kabul etmesini engeller [19].

2.3. DDoS Saldırıları İçin Kullanılan Araçlar ve Teknikler *(Tools and Techniques Used for DDoS Attacks)*

DDoS saldırıları için kullanılan çeşitli araçlar ve teknikler bulunmaktadır. Bu bölümde, en yaygın ve etkili DDoS saldırı yöntemlerinden bazıları incelenecektir. Bu araç ve teknikler, saldırganların hedef sistemleri etkisiz hale getirmek için kullandıkları temel yöntemleri oluşturur.

2.3.1. Botnetler *(Botnets)*

Botnetler, zararlı yazılımlarla ele geçirilmiş bilgisayar ağlarıdır. Saldırganlar, bu bilgisayarları koordine ederek hedefe büyük miktarda trafik gönderir. IoT cihazlarını hedef alarak, bu cihazları ele geçirir ve geniş çaplı DDoS saldırıları gerçekleştirir. Mirai botneti, 2016 yılında Dyn DNS hizmetine yapılan saldırıda kullanılmıştır [20].

2.3.2. Amplifikasyon teknikleri *(Amplification techniques)*

Amplifikasyon teknikleri, küçük bir istek göndererek büyük bir yanıt alınmasını sağlar. DNS Amplifikasyon saldırılarında; saldırgan, sahte IP adresiyle DNS sunucularına küçük bir istek gönderir. DNS sunucuları, bu isteğe büyük yanıtlar vererek hedefi aşırı yükler [21]. NTP (Network Time Protocol) amplifikasyon saldırıları, küçük bir istek göndererek büyük bir yanıt alınmasını sağlayan bir saldırı türüdür. Saldırgan, NTP sunucusuna "MONLIST" komutu içeren küçük bir istek gönderir. Bu komut, NTP sunucusunun son 600 istemci IP adresini döndüren bir yanıt oluşturmasına neden olur. Gönderilen MONLIST isteği yaklaşık 64 bayt iken, yanıt paketleri toplamda 100'den fazla 482 baytlık yanıt paketine dönüşebilir. Bu da yaklaşık 1:200 oranında bir amplifikasyon sağlar [22].

2.3.3. Yönlendirilmiş Saldırılar *(Reflected Attacks)*

Yönlendirilmiş saldırılar, saldırganın hedefe doğrudan saldırmak yerine, üçüncü taraf bir sunucuya sahte bir istek göndererek hedefe yanıtın iletilmesini sağlar. DNS yönlendirilmiş saldırılarda; saldırgan, sahte IP adresiyle DNS sunucularına istek gönderir. Sunucular, hedef IP'ye yanıt gönderir ve hedefi aşırı yükler [23]. NTP yönledirilmiş saldırılarda; saldırgan, sahte IP adresiyle NTP sunucularına istek gönderir. Sunucular, hedef IP'ye büyük yanıtlar gönderir ve hedefi aşırı yükler [24].

2.4. DDoS Saldırılarının Ağ Performansı Üzerindeki Teknik Etkileri *(The Technical Effects of DDoS Attacks on Network Performance)*

DDoS saldırıları, ağ performansını ciddi şekilde etkileyebilir. Bu etkiler arasında ağ gecikmeleri, paket kaybı, bant genişliği tükenmesi ve hizmet kesintileri yer alır.

2.4.1. Ağ Gecikmeleri *(Latency)*

DDoS saldırıları, ağdaki veri paketlerinin hedefe ulaşma süresini artırarak ağ gecikmelerine neden olur. Bu gecikmeler, ağ cihazlarının aşırı yüklenmesi ve bekleme sürelerinin artması sonucu oluşur.

Queueing Delay (Kuyruk Gecikmesi). Ağ cihazları, büyük miktarda gelen trafiği işleyemez hale gelir ve paketler işlenmek üzere kuyrukta bekler. Bu durum, veri iletiminde gecikmelere neden olur [25].

2.4.2. Paket Kaybı *(Packet Loss)*

Aşırı trafik, ağ cihazlarının kapasitesini aştığında, cihazlar daha fazla paket işleyemez hale gelir ve bu da paket kaybına neden olur.

Buffer Overflow (Tampon Taşması). Yönlendirici tamponları dolduğunda, yeni gelen paketler düşürülür ve paket kaybı yaşanır. Bu durum, saldırı sırasında ağın genel performansını ve hizmet kalitesini düşürür.

2.4.3. Bant Genişliği Tükenmesi *(Bandwidth Exhaustion)*

Volumetrik saldırılar, ağın tüm bant genişliğini tüketerek diğer trafiğin geçişine engel olur.

2.4.4. Bağlantı Doygunluğu *(Link Saturation)*

Saldırı trafiği, ağ bağlantılarının taşıma kapasitesini aşar ve bağlantılar tamamen dolar. Bu, saldırı trafiği dışında hiçbir trafiğin geçememesi anlamına gelir. Bu da hizmet kesintilerine ve kullanıcıların hizmete erişememesine neden olabilir [26].

3. Yöntem *(Method)*

Bu çalışmanın amacı, farklı lokasyonlardan gerçekleştirilen DDoS saldırılarının ağ performansına etkilerini gözlemlemek ve Ddosphere aracının bu konudaki yeteneklerini araştırarak uygulamalı bir şekilde test etmektir. Çalışmada kullanılan araç olan Ddosphere, özelleştirilmiş bir DDoS saldırı simülasyon aracıdır. Saldırıların tasarlanması, uygulanması ve sonuçlarının analiz edilmesinde kullanılmıştır.

Ddosphere, kullanıcıların DDoS saldırı testlerini kolayca tasarlayabilmesini, uygulayabilmesini ve sonuçları analiz edebilmesini sağlayan güçlü bir platformdur. Kullanıcı dostu arayüzü ve gelişmiş özellikleri ile Ddosphere, siber güvenlik alanında DDoS saldırı testlerinin gerçekleştirilmesinde önemli avantajlar sunmaktadır. Bu platform, saldırıların gerçek zamanlı olarak izlenmesi, çeşitli metriklerle raporlanması ve farklı saldırı türlerinin karşılaştırılabilmesi gibi özellikler sunar.

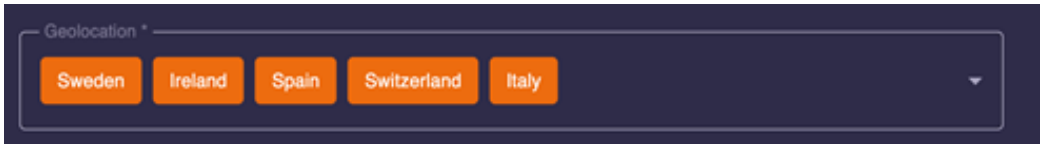
Bu çalışmada, aynı hedef URL'lere yapılan saldırılar incelenmiş ve iki farklı test gerçekleştirilmiştir. Bu testler, Ddosphere'in saldırı tiplerinden bağımsız olarak etkinliğini ve ağ performansına etkilerini ölçmeyi amaçlamıştır. Uygulanan yöntemler aşağıda detaylandırılmıştır:

3.1. Ddosphere ve Saldırı Tipleri *(Ddosphere and Attack Types)*

3.1.1. Saldırı Tipleri *(Attack Types)*

Ddosphere, geniş bir yelpazede yaklaşık 90 saldırı tipi sunar. Bu çalışmada, saldırı tiplerinden bağımsız olarak tek lokasyon ve çoklu lokasyon saldırıları gerçekleştirilmiştir (Şekil 1 ve Şekil 2).

Şekil 1. Tekli Lokasyon *(Single Location)*



Şekil 2. Çoklu Lokasyon *(Multiple Locations)*

3.1.2. Lokasyon Seçimi *(Location Selection)*

Çalışmada, çoklu lokasyon saldırıları için beş farklı coğrafi konum seçilmiştir. Bu seçim, gerçekçi bir DDoS botnet saldırısını simüle etmek için yapılmıştır. Farklı coğrafi konumlar, saldırıların dünya

çapında çeşitli noktalardan gerçekleştirilebilmesi ve ağ performansının bu farklılıklar karşısında nasıl değiştiğinin gözlemlenmesi amacıyla seçilmiştir.

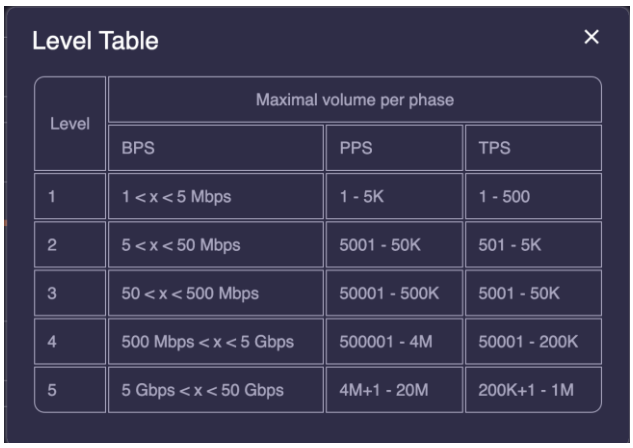
3.2. Saldırı Trafiği Modelleme *(Attack Traffic Modeling)*

3.2.1. Volumetrik Saldırılar *(Volumetric Attacks)*

Saldırılar, volumetrik saldırılar olarak planlanmış ve hedef sistemin bant genişliği ve kaynaklarını tüketmeyi amaçlamıştır. Bu tür saldırılar, ağ trafiğini büyük ölçüde artırarak hedef sistemin hizmet veremez hale gelmesini hedefler.

3.2.2. Saldırı Seviyeleri *(Attack Levels)*

Ddosphere'de saldırıların etkisi, farklı seviyelere göre değişiklik göstermektedir. Her seviyede, gönderilen trafik miktarı (BPS), paket sayısı (PPS) ve işlem sayısı (TPS) artış göstermektedir. Aşağıdaki tabloda, her seviye için belirlenen aralıklar verilmiştir (Şekil 3).


Level Table

Level	Maximal volume per phase		
	BPS	PPS	TPS
1	1 < x < 5 Mbps	1 - 5K	1 - 500
2	5 < x < 50 Mbps	5001 - 50K	501 - 5K
3	50 < x < 500 Mbps	50001 - 500K	5001 - 50K
4	500 Mbps < x < 5 Gbps	500001 - 4M	50001 - 200K
5	5 Gbps < x < 50 Gbps	4M+1 - 20M	200K+1 - 1M

Şekil 3. Saldırı seviyeleri *(Attack Levels)*

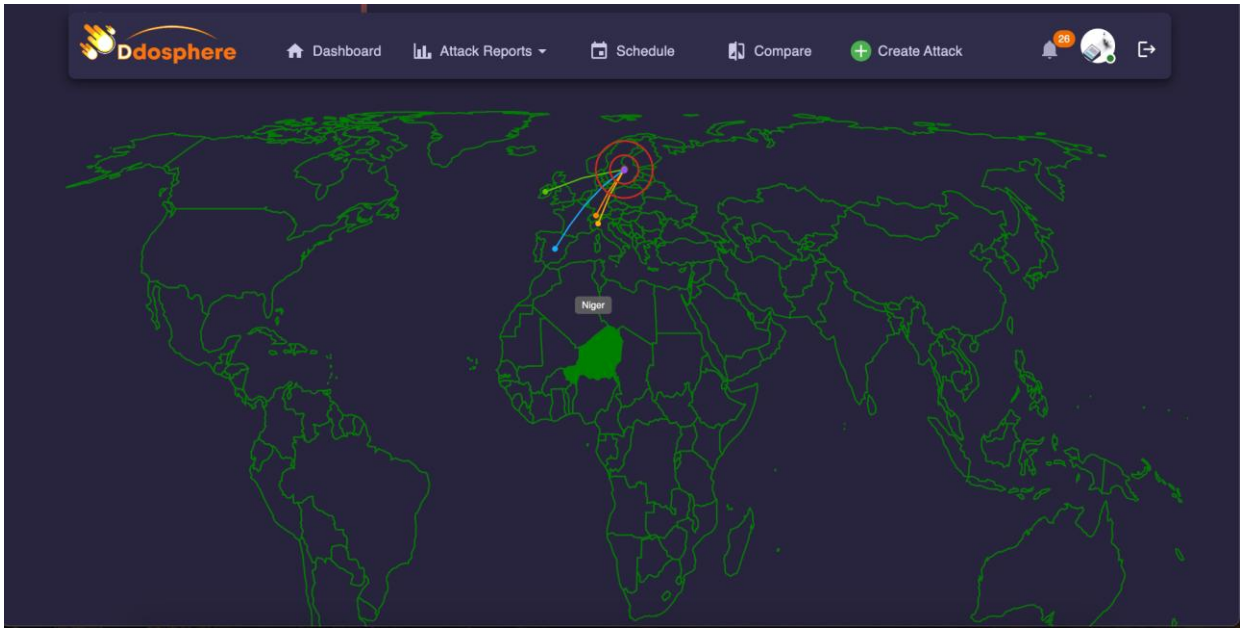
3.3. Test Altyapısı *(Test Infrastructure)*

3.3.1. Dağıtık Mimari *(Distributed Architecture)*

Kubernetes, Docker ve Amazon teknolojileri kullanılarak dağıtık bir mimari oluşturulmuş, farklı sunucular ve coğrafi konumlardan saldırılar gerçekleştirilmiştir. Bu teknoloji, saldırıların esnek bir şekilde yönetilmesini ve ölçeklenmesini sağlar. Kubernetes, konteynerleştirilmiş uygulamaların otomatik dağıtımı, ölçeklenmesi ve yönetimi için kullanılmıştır. Docker, uygulamaların konteynerleştirilmesi için kullanılmıştır. Amazon EC2 bulut sunucuları, farklı coğrafi konumlarda saldırı kaynaklarını simüle etmek için kullanılmıştır.

3.3.2. Canlı Saldırı İzleme *(Live Attack Monitoring)*

Ddosphere, saldırı sırasında anlık olarak gönderilen trafik miktarını ve sistemin sağlık durumunu izleyebilme özelliği sunar. Bu, saldırının etkilerinin gerçek zamanlı olarak değerlendirilmesini sağlar. Anlık izleme sayesinde, saldırı sırasında ne kadar trafik gönderildiği ve hedef sistemin bu trafik karşısındaki durumu sürekli olarak takip edilebilir (Şekil 4).



Şekil 4. Anlık İzleme Sistemi *(Real-Time Monitoring System)*

3.4. Testlerin Gerçekleştirilmesi *(Conducting the Tests)*

3.4.1. Tek Lokasyon Saldırısı *(Single Location Attack)*

Sadece bir sunucudan gelen saldırı trafiği kullanılmıştır. Bu test, tek bir kaynaktan gelen saldırıların sistem üzerindeki etkilerini değerlendirmek için yapılmıştır.

3.4.2. Çoklu Lokasyon Saldırısı *(Multiple Location Attack)*

Beş farklı coğrafi konumdan gelen saldırı trafiği kullanılmıştır. Bu test, dağıtık bir saldırı ortamında sistemin nasıl tepki verdiğini anlamak için yapılmıştır.

3.5. Performans Metrikleri *(Performance Metrics)*

3.5.1. Gecikme Süresi *(Latency)*

Saldırı öncesi ve sonrası ağ gecikme süreleri karşılaştırılmıştır. Gecikme süresi, ağın ne kadar hızlı yanıt verdiğini ve saldırı altında ne kadar yavaşladığını gösterir. Gecikme süresi, ICMP echo request/reply (ping) kullanılarak ölçülmüştür.

3.5.2. Bant Genişliği Kullanımı *(Bandwidth Usage)*

Saldırı sırasında kullanılan bant genişliği miktarı incelenmiştir. Bu, saldırının ne kadar yoğun olduğunu ve sistemin bant genişliğini ne kadar tükettiğini gösterir. Bant genişliği kullanımı, ağ trafiği izleme araçları (örneğin, iftop veya netflow) kullanılarak ölçülmüştür.

3.5.3. Servis Kesintisi *(Service Interruption)*

Saldırı nedeniyle meydana gelen olası servis kesintileri kaydedilmiştir. Bu, saldırının sistemde ne kadar süreyle hizmet kesintisine yol açtığını gösterir. Servis kesintileri, hedef sistemin yanıt vermemesi veya HTTP 503 (Service Unavailable) hataları döndürmesi durumunda kaydedilmiştir.

3.6. Gelişmiş Raporlama ve Karşılaştırma *(Advanced Reporting and Comparison)*

3.6.1. Saldırı Sonrası Raporlama *(Post-Attack Reporting)*

Saldırı sonrasında Ddosphere, gelişmiş raporlama özellikleri sunar. Bu raporlarda, saldırı sırasında gönderilen trafik miktarı, paket kaybı, gecikme süresi ve bant genişliği kullanımı gibi parametreler detaylı bir şekilde analiz edilir.

3.6.2. Rapor Karşılaştırma *(Report Comparison)*

Birden fazla DDoS saldırısının raporları karşılaştırılabilir, bu sayede zaman içindeki değişimler ve farklı saldırı tiplerinin etkileri değerlendirilebilir. Rapor karşılaştırmaları, sistemin farklı saldırı senaryolarına karşı ne kadar dayanıklı olduğunu gösterir.

3.6.3. Zamanlayıcı Kullanımı *(Use of Timer)*

Ddosphere, saldırıların belirli zamanlarda otomatik olarak başlatılabilmesi için zamanlayıcı kurma özelliği sunar. Bu özellik, saldırı testlerinin planlı bir şekilde gerçekleştirilmesini ve sistemin sürekli olarak test edilmesini sağlar.

3.7. Ddosphere ve Diğer Simülasyon Araçları Karşılaştırması *(Comparison of Ddosphere and Other Simulation Tools)*

Ddosphere, Dağıtık Hizmet Reddi (DDoS) saldırılarını simüle etmek için geliştirilmiş bir araçtır. Piyasada LOIC, HOIC, HULK gibi çeşitli DDoS simülasyon araçları bulunmaktadır. Ddosphere'i diğerlerinden ayıran temel farklar, avantajlar ve dezavantajlar aşağıda detaylandırılmıştır (Tablo 2).

3.7.1. Temel Farklar *(Key Differences)*

Mimari ve Ölçeklenebilirlik: Ddosphere, dağıtık ve ölçeklenebilir bir mimariye sahiptir. Bu, çok daha büyük ve karmaşık DDoS saldırılarını simüle etmesine olanak tanır. LOIC ve HOIC gibi araçlar genellikle tek bir makineden çalışır ve ölçeklenebilirlikleri sınırlıdır [4].

Saldırı Türleri ve Özelleştirme: Ddosphere, çeşitli DDoS saldırı türlerini (örneğin, TCP Flood, UDP Flood, HTTP Flood) destekler ve saldırı parametrelerinin detaylı bir şekilde özelleştirilmesine imkan verir. Diğer araçlar genellikle daha sınırlı saldırı türleri sunar ve özelleştirme seçenekleri daha azdır [6].

Gerçekçilik ve Simülasyon Doğruluğu: Ddosphere, gerçek dünya senaryolarına daha yakın simülasyonlar oluşturmayı hedefler. Ağ trafiği ve saldırı desenlerini daha gerçekçi bir şekilde taklit eder. LOIC ve HOIC gibi araçlar, basit ve temel saldırılar üretir, bu da gerçekçiliklerini azaltır [20].

Kullanım Kolaylığı ve Arayüz: Ddosphere, kullanıcı dostu bir arayüz ve kolay yapılandırma seçenekleri sunar. Diğer araçların arayüzleri daha karmaşık veya teknik bilgi gerektirebilir [10].

Tablo 2. Karşılaştırma tablosu *(Comparison Table)*

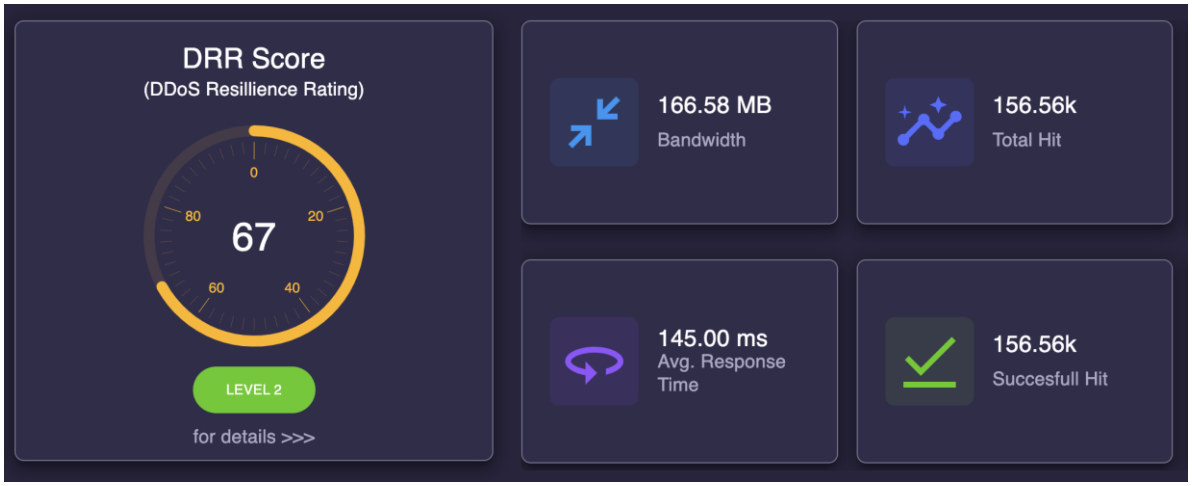
Özellik	Ddosphere	LOIC	HOIC	HULK
Mimari	Dağıtık, Ölçeklenebilir	Tek Makine	Tek Makine	Tek Makine
Saldırı Türleri	Geniş ve Özelleştirilebilir	Sınırlı	Sınırlı	Sınırlı
Ölçeklenebilirlik	Yüksek	Düşük	Düşük	Düşük
Gerçekçilik	Yüksek	Düşük	Düşük	Düşük
Kullanım Kolaylığı	Yüksek	Orta	Orta	Orta
Özelleştirme	Yüksek	Düşük	Düşük	Düşük

4. Bulgular *(Findings)*

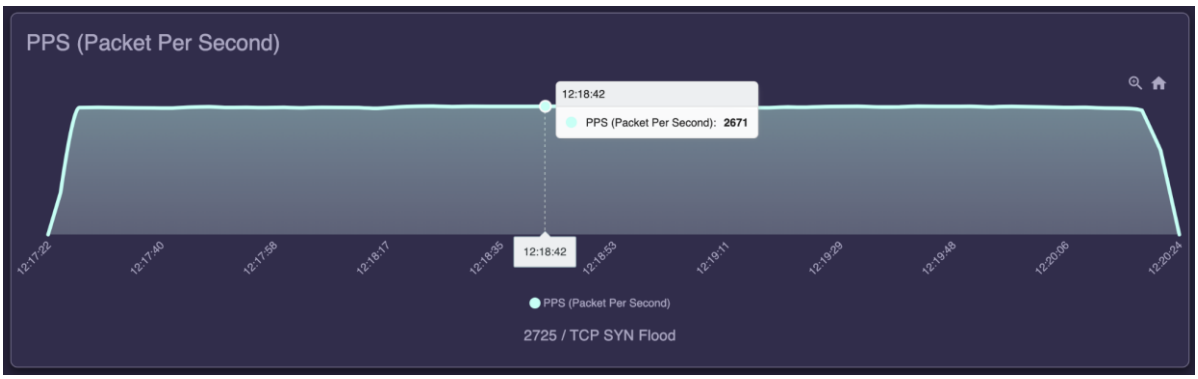
Bu bölümde, yapılan testlerin sonuçları incelenerek tek ve çoklu konumlu saldırıların ağ performansı üzerindeki etkileri karşılaştırmalı olarak sunulmaktadır.

4.1. Tek Lokasyon Saldırısı *(Single Location Attack)*

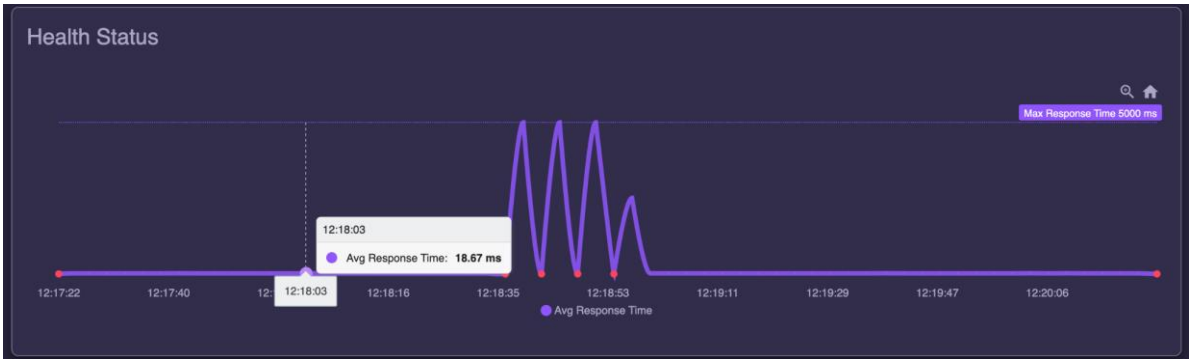
Gecikme Süresi. Ortalama gecikme süresi 18 ms'den 145 ms'ye yükselmiştir (Şekil 5). Bant Genişliği Kullanımı. Saldırı trafiği 166.58 MB olarak ölçülmüştür (Şekil 6). Servis Kesintisi. Kısa süreli (yaklaşık 24 saniyelik) servis kesintileri raporlanmıştır (Şekil 7).



Şekil 5. Tek lokasyon saldırısı sırasındaki gecikme süresi değişimi *(Latency variation during the single location attack)*



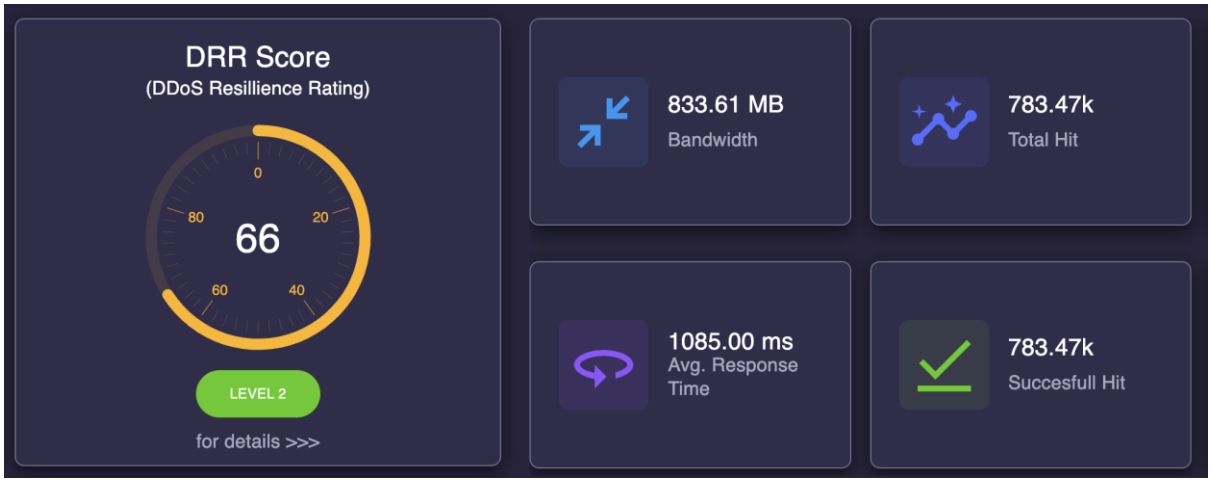
Şekil 6. Tek lokasyon saldırısı sırasındaki bant genişliği kullanımı *(Bandwidth usage during the single location attack)*



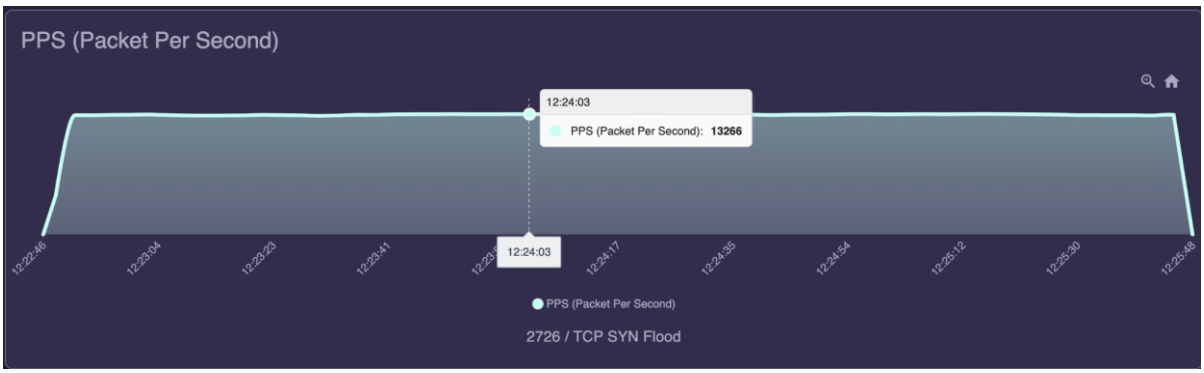
Şekil 7. Tek lokasyon saldırısı sırasında raporlanan servis kesintileri *(Service interruptions reported during the single location attack)*

4.2. Çoklu Lokasyon Saldırısı *(Multiple Location Attack)*

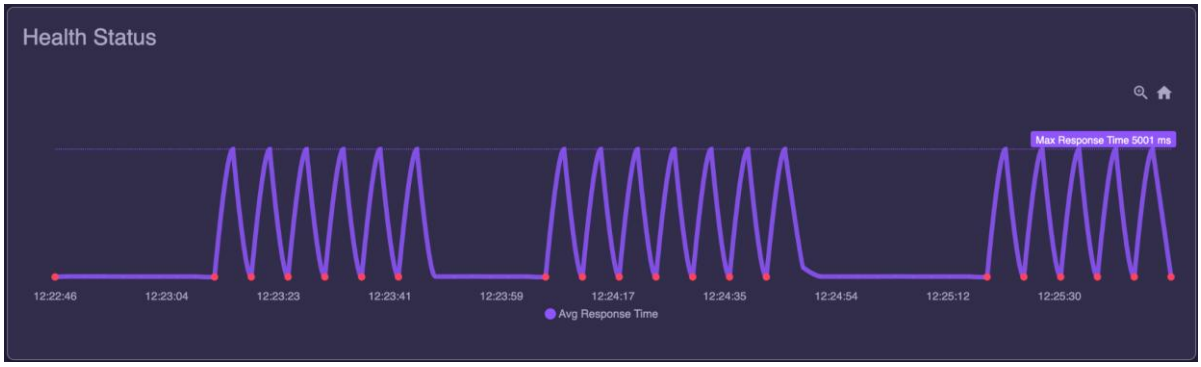
Gecikme Süresi. Ortalama gecikme süresi 18 ms'den 1045 ms'ye çıkmıştır (Şekil 8). Bant Genişliği Kullanımı. Saldırı trafiği 833.61 MB olarak ölçülmüştür (Şekil 9). Servis Kesintisi. Uzun süreli (yaklaşık 108 saniyelik) servis kesintileri yaşanmıştır (Şekil 10).



Şekil 8. Çoklu lokasyon saldırısı sırasındaki gecikme süresi değişimi *(Latency variation during the multiple location attack)*



Şekil 9. Çoklu lokasyon saldırısı sırasındaki bant genişliği kullanımı *(Bandwidth usage during the multiple location attack)*



Şekil 10. Çoklu Lokasyon Saldırısı Sırasında Raporlanan Servis Kesintileri *(Service interruptions reported during the multiple location attack)*

4.3. Genel Değerlendirme *(Overall Evaluation)*

4.3.1. Tek lokasyon vs. çoklu lokasyon *(Single Location vs. Multiple Location)*

Tek lokasyondan gelen saldırılar, çoklu lokasyon saldırılarına göre daha az zararlı olmuştur. Çoklu lokasyondan gerçekleştirilen saldırılar, ağ performansını ciddi şekilde düşürmüş ve daha fazla hizmet kesintisine yol açmıştır.

4.3.2. Ddosphere'in etkinliği *(Effectiveness of Ddosphere)*

Ddosphere, geniş saldırı yelpazesi, dağıtık saldırı kapasitesi ve gelişmiş raporlama özellikleri ile ağ performansını değerlendirmede etkili bir araç olarak görülmüştür.

Bu çalışma, Ddosphere'in sunduğu geniş saldırı çeşitliliği, dağıtık saldırı kapasitesi ve gelişmiş raporlama özellikleri ile tek lokasyondan yapılan saldırılara kıyasla, çoklu lokasyonlardan yapılan DDoS saldırılarının ağ performansına çok daha ciddi etkiler yarattığını göstermiştir. Çalışma sonucunda, çoklu lokasyon saldırılarının ağ performansını daha fazla düşürdüğü ve daha uzun süreli hizmet kesintilerine yol açtığı belirlenmiştir. Bu bulgular, ağ performansını korumak ve hizmet kesintilerini en aza indirmek için daha güçlü ve dağıtık saldırılara karşı daha dirençli savunma mekanizmalarının geliştirilmesi gerektiğini ortaya koymaktadır.

5. Sonuç *(Conclusion)*

Sonuç olarak, bu çalışma, çoklu lokasyonlardan gelen DDoS saldırılarının ağ performansı üzerindeki yıkıcı etkilerini net bir şekilde ortaya koymuştur. Tek lokasyondan gelen saldırılara kıyasla, çoklu lokasyonlardan gerçekleştirilen saldırılar, ağ performansını daha fazla düşürmüş ve daha uzun süreli hizmet kesintilerine yol açmıştır. Bu bulgular, ağ güvenliğini sağlamak ve hizmet kesintilerini minimize etmek için daha güçlü ve dirençli savunma mekanizmalarının geliştirilmesi gerektiğini göstermektedir.

Ddosphere aracı, sunduğu geniş saldırı yelpazesi ve dağıtık saldırı kapasitesi ile bu tür senaryo ve simülasyonlarda etkili bir araç olduğunu kanıtlamıştır. Bu çalışma, ağ yöneticileri ve siber güvenlik uzmanları için değerli içgörüler sunulmakta olup, gelecekteki siber tehditlere karşı hazırlıklı olmak adına savunma stratejilerinin gözden geçirilmesi ve güçlendirilmesi gerektiğini vurgulamaktadır. Siber güvenlik alanındaki bu tür araçların önemi, sadece mevcut tehditlere karşı değil, aynı zamanda ağ performansını optimize etmek ve olası hizmet kesintilerini en aza indirmek için yapılacak iyileştirmeler açısından da kritik bir rol oynamaktadır.

Bu çalışma, ağların DDoS saldırılarına karşı korunması için daha geniş çaplı araştırmaların ve geliştirmelerin gerekliliğini de ortaya koymaktadır. Gelecekteki araştırmalar, bu tür saldırılara karşı daha sofistike ve entegre savunma mekanizmalarının geliştirilmesine katkı sağlayabilir.

Teşekkür ve Finansman ***(Acknowledgments and Funding)***

Bu çalışmanın özet hali, 21. UBAK Uluslararası Bilimsel Araştırmalar Kongresi'nde (12-13 Ekim 2024) sunulmuştur.

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alpha
Journal of Engineering and Applied Sciences
(AJEAS)
e-ISSN: 3023-6002

Alfa Mühendislik ve Uygulamalı Bilimler Dergisi
(2025) 3/1: 51– 74

Review Article

DOI: 10.70988/ajeas.1606187

Received: 12/23/2024

Accepted: 04/14/2025

Published: 04/30/2025

Investigation of Common Analysis Methods for Detecting Illicit Drugs in Wastewater

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Abstract

In this study, research was carried out using analytical devices used to detect illicit drugs that threaten public health. Articles on detecting illicit drugs worldwide were reviewed in the last five years. In 2022, one in 18 people, or approximately 292 million people, had used illicit drugs in the past year, and this number has increased by more than 20% considering the past decade. Approximately 30 million people used amphetamines, and 60 million people used opioids in the past year. Drug use, especially opioid use, remained the largest global burden of disease. Wastewater-based epidemiology is an innovative and promising discipline that has recently been used for individual biomonitoring and estimating the amount and type of illicit drug use in the population. Many disciplines, including analytical chemistry, physiology, biochemistry, sewage engineering, spatial epidemiology, statistics, and pharmaceutical/public health epidemiology, are used to estimate the prevalence of illicit drugs and their metabolic products in wastewater. This study aimed to review the articles on the detection of illicit drugs in wastewater, determine the most used analytical devices between 2017-2023, present a summary of the devices used for illicit drug detection, and provide a quick overview of the literature.

Keywords: *Illicit drugs, Wastewater based epidemiology, Analytical methods, Analytical devices*

Atık Sularda Yasa Dışı Uyuşturucu Maddelerin Tespitinde Kullanılan Yaygın Analiz Metotlarının İncelenmesi

Özet

Bu çalışmada halk sağlığını tehdit eden yasa dışı uyuşturucu maddelerin tespitinde kullanılan analitik cihazların araştırılması yapılmıştır. Son beş yılda dünya çapında yasa dışı uyuşturucuların tespitine yönelik makaleler incelenmiştir. 2022 yılında geçen bir yıl boyunca 18 kişiden biri veya yaklaşık 292 milyon kişi yasa dışı uyuşturucu madde kullanmıştır ve bu sayı son on yıla göre % 20'den fazla artmıştır. Geçen bir yılda yaklaşık 30 milyon kişi amfetamin, 60 milyon kişi opioid kullanmıştır. Uyuşturucu madde kullanımı, özellikle de opioid kullanımı, en büyük küresel hastalık yükü olmaya devam etmektedir. Atık su epidemiyolojisi, son zamanlarda bireysel biyoizleme ve popülasyondaki yasa dışı madde kullanımının miktarını ve türünü tahmin etmek için kullanılan yenilikçi ve umut verici bir disiplindir.Analitik kimya, fizyoloji, biyokimya, atık su mühendisliği, mekansal epidemiyoloji, istatistik ve farmasötik/halk sağlığı epidemiyolojisi dahil olmak üzere farklı disiplinler atık sularda yasa dışı madde ve metabolik ürünlerinin prevelansını tahmin etmekte kullanılmaktadır. Bu çalışmada, 2017-2023 yılları arasında atıksularda yasa dışı uyuşturucu maddelerin tespiti ile ilgili makalelerin incelenmesi, en çok kullanılan analitik cihazların belirlenmesi, yasa dışı uyuşturucu madde tespiti için kullanılan cihazların özetinin sunulması ve literatüre hızlı bir genel bakış sağlanması amaçlanmıştır.

Anahtar kelimeler: *Yasa dışı uyuşturucu maddeler, Atık su bazlı epidemiyoloji, Analitik metotlar, Analitik cihazlar*

Citation: Ş. Şenol, "Investigation of Common Analysis Methods for Detecting Illicit Drugs in Wastewater", AJEAS. (2025) 3(1): 51-74. http://dx.doi.org/10.70988/ajeas.1606187

1. Introduction

Modern societies consume a wide variety of chemical products that can potentially cause toxic effects on receiving water, including pharmaceuticals, illegal drugs, and food additives, among others. Some of these illicit drugs are emerging contaminants of concern (CECs). The development and application of analytical methodologies, such as multi-residue methods, enable the detection of the presence and concentration of various chemicals in the wastewater and affected water systems. Such studies are used in early warning systems and/or to evaluate different chemical classes in spatiotemporal variations [1-3]. The consumption of different types of illicit drugs and new psychoactive substances (NPS) has risen in recent years and has become a global problem due to its effects on public health, safety, and the economy [4].

Epidemiology, and especially wastewater-based epidemiology, have great importance in identifying the rates of illicit drug use in wastewater, as well as providing more reliable, objective, and realistic results. Wastewater-based epidemiology makes an effective detection using illicit drug biomarkers in wastewater samples. Analytical devices used to detect illicit drugs in wastewater are becoming increasingly important for the measurements to be precise and reliable [5, 6].

1.1. Illicit drug use in the world

Illicit drug use is on the rise, with different types every year around the world. In 2021, 1 in 17 people in the age group of 15-64 used illicit drugs in the past 12 months. The number of people using illicit drugs in 2021 is estimated to be 296 million. Cannabis was the most used illicit drug, with 219 million users in 2021, and the number of cannabis users has increased by 21% in the last decade. Illicit drug use is increasing worldwide, and although men use cannabis more than women globally (approximately 70%), gendered patterns of illicit drug use vary in some subregions. In North America, 42% of cannabis users are women. According to the 2023 World Drug Report, it is estimated that 22 million people used cocaine, 36 million people used amphetamine, and 20 million people used "ecstasy" type drugs in the past year in 2021. Opioids remain the group of illicit drugs with the highest rates of serious drug-related harm, including fatal overdoses. Approximately 60 million people used non-medical opioids in 2021, of whom 31.5 million used opiates [7-8]. The data from the 2024 World Drug Report shows 292 million people in the world used drugs in 2022, and the number of people using drugs has increased by approximately 20% for more than 10 years. In 2022, drug use disorder was detected in 64 million people in the world, and only 1 in 11 people received treatment. In 2022, there were 13.9 million people who injected illegal drugs. Cannabis (228 million users) is the most used illicit drug worldwide. 60 million people used opioids, amphetamines used by 30 million people, and 23 million people used cocaine, and ecstasy is used by 20 million people in 2022 [9].

Türkiye continues to be an important transit country for drug trafficking due to its geographical location. Illicit drug seizures are increasing in Türkiye. In addition, drugs are an important problem not only in the world but also in Türkiye. According to Turkish Drug Report, when individuals receiving treatment in 2023 were examined in terms of the types of substances they used for treatment; 28% were found to have received treatment for heroin, 37.1% for methamphetamine, 11.2% for marijuana, 4.9% for synthetic cannabinoids, 4.2% for other opiates, 4% for cocaine, 0.7% for ecstasy, 1.1% for volatile substances, and 8.9% for other substances. The average age of individuals applying for treatment was determined as 29.78. When the distribution of those receiving treatment by age group was examined, it was determined that those applying for treatment were concentrated between the ages of 25-34. When the distribution of those receiving inpatient treatment by gender was examined in 2023, it was reported that 90.3% were male and 9.7% were female [10].

1.2. Wastewater-based epidemiology

Illicit drugs and their metabolic products in municipal wastewater are used to estimate the prevalence of use in the community, employing various research disciplines, including analytical chemistry, physiology, biochemistry, sewage engineering, spatial epidemiology, statistics, and drug/public health epidemiology. Wastewater-based epidemiology is a promising discipline that has recently been used for individual biomonitoring and estimating the quantity and type of illicit drug use in society [11, 12].

Wastewater-based epidemiology also plays a key role in detecting new-generation psychoactive substances used in educational institutions and determining the prevalence of illegal drug use during weekends, national holidays, festivals, and epidemics such as COVID-19 [5].

According to the European Monitoring Centre for Drugs and Drug Addiction/ European Union Drug Agency (EMCCDA/EUDA) wastewater analysis explanations (Figure 1), the illicit drug to be detected is carried out by taking samples from wastewater treatment points that represent the population at certain times. Subsequently, daily drug use amounts are calculated using common calculation methods [11].

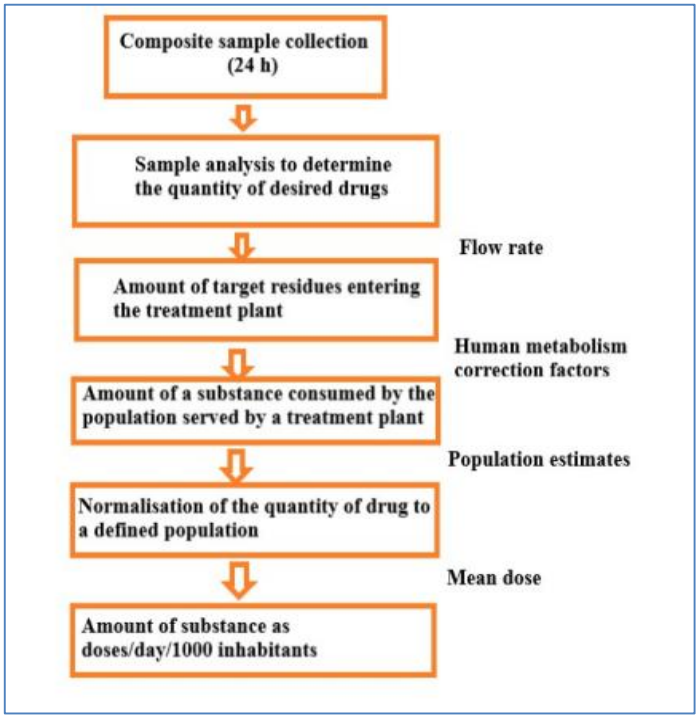

Figure 1. Steps to determine illicit drugs in wastewater [11]

According to the calculation method described above, composite samples are collected for 24 hours. The samples are analysed with the help of the specified analytical device to determine the concentrations of the drug residues to be determined. Following this, illicit drug use is estimated by back calculation by multiplying the concentration of each target drug residue (nanogram/liter) by the corresponding sewage flow (liter/day). A correction factor is taken into account in the calculation for each illicit drug. In the last step, the obtained data is divided by the population served by the wastewater treatment plant, which indicates the amount of substance consumed per day per 1000 people. Population estimates can be calculated using different biological parameters, census data, the number of houses in the residential area, etc. It should be noted that the general variability of different estimates

can often be very high. Although this method represents a certain population use, it can be applied in festival periods, Ramadan periods, prisons, small settlements, workplaces, and schools. When used in small communities, this method can pose an ethical risk because it can detect a certain possible group in the small community, and for this reason, the SCORE group has published ethical guidelines for wastewater-based epidemiology and related fields [11].

Potential risks in prisons in the context of detecting illicit drugs in wastewater may include developing strategies to prevent drug consumption by prison staff, such as eliminating contact visits for prisoners' families. In this case, if emotional problems may occur as the precautions to be taken are increased, and if they harm those who do not consent to the study, an ethical problem may occur. Another problem is the stigmatization of prisoners, ex-prisoners, and their families. If the WBE research findings are not managed effectively in media reports about illicit drug consumption in prisons, this may cause negative feelings in society, prisoners may be embarrassed, and problems may occur in the process of reintegrating ex-prisoners into society [11].

Studies on schools and workplaces may result in the stigmatization and labelling of people in these places because of the findings being included in the relevant reports. Other risks include negative impacts on the reputation of schools or workplaces and economic damage to workplaces. It may be necessary to plan how the research results will be communicated to the media clearly and concisely. Media organizations should be encouraged to use language within the research plan that will persuade participants to emphasize the benefits of the research rather than stigmatizing or labelling [11]. In some cases, mixing samples from multiple sites can be used to overcome the problem of reporting only aggregate data. Or it may be possible to simply omit the name and location where the study was conducted. Additionally, taking samples without permission from a specific building (e.g., prison, school, workplace, hospital) may be an offense or a regulatory problem. This may negatively impact the reputation of the WBE field and the willingness of authorities to support or collaborate with WBE researchers [11].

The method used cannot provide information on the prevalence and frequency of use, main classes of users, and purity of drugs. Additional difficulties arise from uncertainties associated with the behavior of selected biomarkers in sewage, different back-calculation methods, and different approaches to estimating the size of the tested population [13, 16]. For example, caveats in the selection of analytical targets for heroin make monitoring this drug in wastewater more complex than for other substances. Illicit drugs from composite samples are usually analysed for their major urinary metabolites (i.e., substances produced when the body breaks down drugs). However, the specific metabolite of heroin, 6-monoacetylmorphine, is not stable in wastewater. Therefore, the only alternative is to use morphine, which is not a specific biomarker and can be detected after therapeutic use. This highlights the importance of obtaining the most accurate information on morphine use from prescription and/or sales reports [11, 17]. Furthermore, the purity of street drugs varies unpredictably over time and in different locations. Calculating the total amounts of drugs consumed into the corresponding average dose is complex because drugs can be taken by different routes (oral, intravenous) and in widely varying amounts, and their purity levels vary [18].

In particular, differences in flow rates that may occur in rainy and stormy weather and failure to obtain samples of the desired quality may negatively affect the analysis and calculations, or, since the purity of drugs produced illegally and counterfeit cannot be determined, such situations may change the accuracy and precision of the calculations. In the summer months, short-term visits by people who do not live in certain tourist areas and failure to determine the instantaneous or weekly net population may cause differences in the calculations. This can make it difficult to follow the general trend [18].

1.3. Analytical methods

The wide variety of components in wastewater, chemical stability of the substances in wastewater, and various properties such as pKa and hydrophilicity can be a complex process in analysis studies. Therefore, the selection of appropriate analytical methods is essential for accurate determination, so analytical methods are gaining importance in detecting illicit drug accurately [20-22].

Ultra-performance Liquid Chromatography (UPLC), Ultra-High-Performance Liquid Chromatography (UHPLC), and High-performance Liquid Chromatography (HPLC) are included in LC systems. In UPLC and UHPLC systems based on HPLC techniques, a stationary phase with a smaller chromatographic particle diameter and greater pressure in the column is used. High sensitivity and fast analysis results are obtained from these systems [5, 11-21, 22]. HPLC is of great importance for quantitative and qualitative analysis, playing an important role in the evaluation of pharmaceutical samples, as it is one of the fastest, most flexible, and safest chromatographic analytical techniques in the quality control of pharmaceutical ingredients and chemicals [22]. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) is one of the most selected methods to identify drug residues and drug quantity in wastewater. This analytical approach integrates the techniques of LC with the analysis properties of mass spectrometry. In terms of the low concentrations of drug residues and complexity in wastewater, LC-MS/MS is one of the effective devices due to its effectiveness, selectivity, robustness, and sensitivity. Electrospray ionization (ESI) interfaces generally provide the desired quality of sensitivity [23]. Due to its remarkable reduction in analysis time, rapid separation, and high throughput capacity, UHPLC is attractive for environmental, food, chemical, and pharmaceutical analyses. Ultrafast liquid chromatography (UFLC), while shortening the analysis time, is used with the MS detector for trace amounts of compounds. Its high-pressure resistance, fast scanning speed, enhanced throughput, and less solvent consumption make this device attractive. UFLC operates at a much faster rate than HPLC, providing faster analysis and shorter run times. UFLC provides more accurate and reliable data for complex sample analysis. UFLC often exhibits improved sensitivity and is useful in applications where identifying low-abundance analytes is critical. UFLC typically uses less solvent. As a result, costs are reduced, and a greener strategy is implemented [22].

UPLC has several advantages over HPLC. These include increasing sensitivity while reducing analysis time, reducing solvent usage and operating costs, reducing cycle times in processes, and enabling more throughput using existing resources. Another advantage is that it maintains the resolution performance while providing the selectivity, sensitivity, and variability of LC analysis and using cutting-edge separation materials with small particle sizes for faster analysis [22].

Direct injection (DI) of samples represents a new trend that takes importance in the increased sensitivity of mass spectrometry (MS) devices [24]. Micro-liquid chromatography-tandem mass spectrometry (μLC-MS/MS), which can be utilized for cocaine, ATS, and NPS analysis, has higher ionization efficiency and sensitivity compared to conventional UHPLC due to the low flow rate [25].

Liquid chromatography coupled with high-resolution tandem mass spectrometry (LC-HRMS) is used to determine markers of illicit stimulants in wastewater. LC-HR/MS can be used to detect levamisole, a veterinary anthelmintic found in street cocaine, herbal medicines containing only natural ingredients, designer drugs, and doping agents. LC-HR/MS has successfully detected mislabeled or misrepresented street drugs. Detection of new designer amines, stimulants found in “bath salts” and synthetic cannabinoids is well suited for LC-HR/MS. Liquid chromatography coupled with High-resolution mass spectrometry (LC-HRMS) can be utilized for highly sensitive and reproducible detection of hundreds or thousands of metabolites in a single sample [26, 27]. LC-HRMS is robust, flexible, sensitive, practical, and useful for modern high-throughput laboratories [26, 30].

Flow injection analysis (FIA) combined with high-resolution mass spectrometry (HRMS) is used for the rapid analysis of psychoactive substances found in recreational (illicit drugs, human and veterinary medicines, legal highs) and licit/illicit drugs. FIA and HRMS operating conditions can be adjusted to detect a wide range of psychoactive compounds [28]. QTOF-HRMS technique is a practical method for fast screening of pharmaceutical drugs as it leads to the combination of high-resolution full-scan analysis [29]. Although LC-MS/MS has high sensitivity and selectivity, some limitations exist for multi-compound and multi-class analyses. The most current QqQ instruments available in MS/MS methods allow for low dwell times and a significant increase in the number of passes obtained at a time. Even when working with thousands of contaminants, the acquisition time of each pass is still a limitation in wastewater. The duration of each transition may limit the number of analytes to be detected. The use of LC-MS/MS methods is insufficient to make a general comment regarding the drugs in question. In the LC-MS/MS method, substances present at high levels other than the selected analytes are often ignored [30].

In summary, the most important issue in the selection of devices used in the detection of illicit drugs is the rapid and precise measurement of the illicit drugs to be detected. Another important issue for analysts is that the analysis time is not prolonged. While GS-MS provides high selectivity and sensitivity, derivatization of most drugs and compatibility of biomarkers with GC may not be practical and fast enough. LC-MS can be used to detect more compounds, in addition to being faster and requiring less sampling. LC-MS/MS is frequently used in the detection of drugs in wastewater, and HRMS continues to be used to obtain accurate mass full-spectrum data with its advantageous screening and identification features.

2. Experimental Section

2.1. High-frequency keywords

The most searched words include illicit drugs, wastewater analysis, illicit drug(s), wastewater-based epidemiology, analytical methods, LC-MS/MS, UHPLC_MS/MS, LC-Orbitrap/MS, Direct Injection (DI), UPLC-MS/MS, Solid Phase Extraction (SPE), and LC/HRMS. The most searched words include illicit drugs, wastewater epidemiology, target drug metabolite, and wastewater-based analysis. The international electronic databases, including Google Scholar, Scopus, PubMed Science, and local databases from 2017 up to 2023, were searched. High-frequency keywords in the field of WBE are shown in Fig. 2.

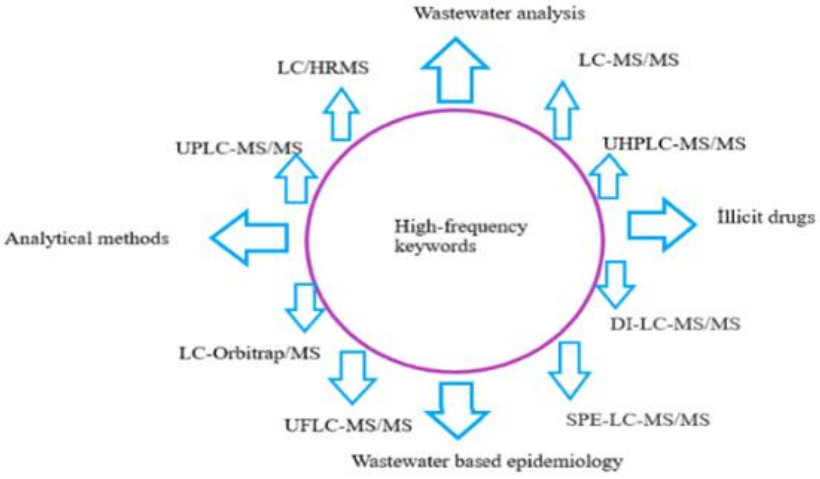

Figure 2. High-frequency keywords in the literature

2.2. Analytical laboratory devices in literature

According to the European Union Drug Agency (EUDA), Liquid chromatography-tandem mass spectrometry (LC-MS/MS) is the most frequently used analytical method to measure drug residues in wastewater. Additionally, considering the expected complexity and low concentrations in wastewater, LC-MS/MS is one of the most powerful techniques for this analysis due to its sensitivity and selectivity [11].

The SCORE group has been organizing an annual monitoring campaign for systematic data assessments through wastewater analysis since 2011. This comprehensive analysis, which supports wastewater analysis, is published by the European Centre for Drugs and Drug Addiction (EMCDDA), European Union Drug Agency (EUDA) in Lisbon, to communicate the results to the scientists or institutions that support it [31,32].

Reliable estimation of accuracy is important, so some laboratories validate laboratory results with the SCORe group to ensure the accuracy of their work. In the study titled "Wastewater-based Monitoring of Illicit Drugs in Cyprus by UPLC-MS/MS: The Impact of the COVID-19 Pandemic", it was stated that the validation of the results was provided by participation in the annual SCORe group validation [35]. In the article titled “Three Years of Wastewater Surveillance for New Psychoactive Substances from 16 Countries”, the WBE protocol was applied for sample collection, storage, and analytical methodology [43].

The validated analytical method of the article “Comparison of Community Illicit Drug Use in 11 Cities of Turkey through Wastewater-based Epidemiology Study” passed the interlaboratory cross-comparison of the SCORE group [49]. In the article titled "Monitoring of Changes in Illicit Drugs, Alcohol, and Nicotine Consumption During Ramadan via Wastewater Analysis”, it was stated that the reliability and accuracy of the sample preparation and LC-MS/MS device complied with the quality criteria determined by the SCORE group [50]. It was stated that all analytical methods used in the study titled "Assessment of Illicit Drugs in Wastewater and Estimation of Drugs of Abuse in Adana Province, Turkey" were validated and cross-checked with the SCORE interlaboratory free comparison test [54].

The analytical method was validated in terms of Limit of Quantification (LOQ), Limit of Detection (LOD), linearity, recovery, and instrument and method repeatability. Instrument and method repeatability were controlled by analysing each sample three times. The linearity of the calibration curves with coefficient of determination $R^2 > 0.9900$, for all illicit drugs [35].

Instrumental detection limits (IDLs) and instrumental quantification limits (IQLs) were obtained by direct injection of decreasing quantities of each illicit drug. IDLs and IQLs were calculated as the concentration-giving peaks for which the signal-to-noise ratio was 3 and 10, respectively. Limits of detection and quantification, intra-day and inter-day precisions, accuracies, and recovery studies were applied to determine the performance of the method [41].

In the study titled “Occurrence of Z-drugs, Benzodiazepines, and Ketamine in Wastewater in the United States and Mexico During the Covid-19 Pandemic”, method detection limits were calculated according to the US Environmental Protection Agency (USEPA, 2016) revised protocol [37]. In the article "Dilute-and-Shoot Approach for The High-Throughput LC-MS/MS Determination of Illicit Drugs in the Field of Wastewater-based Epidemiology" accuracy and precision were evaluated for each influent wastewater (IWW) samples (n = 5) at four concentrations of 0.1, 0.5, 2.5 and 10 µg L^{-1}:

Mean recoveries ranging from 70% to 120% were considered suitable. Individual quality controls (QCs) recoveries ranging from 60% to 140% were considered efficient [39].

In the analytical method study conducted in 11 provinces, it was determined that the method was linear and the correlation coefficient was greater than 0.99. In the studies, the method recovery was determined to be between 85-114% for the illicit drugs studied [39, 41]. Limits of detections (LODs) and LOQs of illicit drugs obtained using US Environmental Protection Agency (USEPA) guidelines (USEPA 2016) [50].

It has been stated that sources such as the International Conference on Harmonization (ICH), the European Medicines Agency (EMA), the International Union of Pure and Applied Chemistry (IUPAC), the Analytical Procedures and Methods Validation for Drugs and Biologics Guidance for Industry, and the Scientific Working Group for Forensic Toxicology (SWGTOX) can be used for analytical validation [41].

The acceptable deviation between empirical and library data was selected using the guideline document "Analytical Quality Control and Method Validation Procedures for Pesticide Residues Analysis in Food and Feed SANTE 11312/2021" [51].

Table 1 includes studies carried out to detect illicit drugs in various countries of the world and at various times. Analytical laboratory devices are selected depending on the type of drug desired, its sensitivity, and factors such as the detection time of metabolites. In general, the LC-MS/MS device was chosen more intensively in the articles examined within the scope of this study.

In addition to Table 1, artificial intelligence and machine learning (ML) methods also play an important role in illicit drug detection from wastewater. In the study, different machine learning models (Support Vector Machines (SVM), eXtreme Gradient Boosting (XGB), Random Forest, Gradient Boosting, K-Nearest Neighbors (KNN)) were successfully used to classify illegally produced drugs according to their infrared spectrum due to their effective, easy and fast applicability [56]. In other studies, conducted on illicit drug detection, it was determined that different models, such as various artificial neural networks, deep learning, elastic net, decision trees, and logistic regression, were used. The determined models were used for different substance classes, including alcohol, cannabis, hallucinogens, tobacco, opioids, sedatives, and hypnotics. Various substance use data from social media platforms and risk factors such as socioeconomic and demographic data, behavior characteristics, and psychopathology data were used for model training, and then the model was tested. Using artificial intelligence models to develop data-driven smart applications can reduce negative consequences related to the process and accelerate the early implementation of interventions. This could help healthcare professionals and drug enforcement officials effectively screen, assess, and predict illicit substance use. Also, the usage of AI and ML supports developing timely preventive activities [57-59].

Table 1. Analytical methods used in the detection of illicit drugs globally

Analysis device/ method	Location	Year/ Sampling period	Types of illicit drugs & NPSs	First author& References
Ultra-High-Performance Liquid Chromatography/ High-resolution mass spectrometry (UHPLC–HRMS)	Taiwan	2023/ 7 March 2023	**Illicit drugs** • Amphetamine • Methamphetamine • Norketamine • Ketamine • Morphine • Codeine • Tapentadol • Meperidine • Levorphanol • Tramadol • Hydromorphone • Dihydromorphine • 4-Methy N, Ndimethylcathinone • Methylenedioxypyrovalerone (MDPV) • 5-(2-Aminoethyl)-2,3-dihydrobenzofuran (5-AEDB) • Bufotenin • N-methyl-2-aminoindane • 1,4-Androstadiene-3,17-dione • Methenolone • Ephedrine • N-Methylephedrine **NPSs** • Mephedrone 4’-chloro alphapyrrolidinopropiophenone (4-Cl-α-PPP)	Chen et al. [33]
Liquid Chromatography coupled to tandem mass spectrometry (LC-MS/MS)	Germany	2023/ from April 2020 to December 2021	• The metabolites of cocaine (Benzoylecgonine) • Methamphetamine • MDMA • Nicotine (cotinine) • Gabapentin • Metoprolol • Amphetamine • Carbamazepine	Oettel et al. [34]
UPLC-MS/MS	Cyprus	2023/ 20-26 April 2021, 19–25 July 2021, 11–17 October 2021, 25 December 2021–2 January 2022	• MDMA • Amphetamine • Cocaine • Methamphetamine	Psichoudaki et al. [35]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	Location	Year/ Sampling period	Types of illicit drugs & NPSs	First author& References
LC-HRMS	Cadiz Bay (Spain)	2023/Daily during 1 week in June 2021	• Cocaine and its metabolite benzoylecgonine • Tapentadol • Tramadol • Cannabidiol (CBD) • Delta 9-Tetrahydrocannabinol (THC) • 2C-E (2,5-Dimethoxy-4-ethyl phenethylamine) • Cocaethylene	Santana Viera et al. [36]
Liquid Chromatography	Mexico and USA (in different states from the US and 14 states from Mexico)	2023/July to October 2020	• Benzodiazepines • Ketamine	Adhikari et al. [37]
LC-HRMS LC-Orbitrap/MS	South Korean	2023	**Traditional Psychoactive Substances and Their Metabolites** • Ketamine • Zolpidem phenyl-4-COOH • Tramadol • Phenmetrazine • Phentermine • Methamphetamine • Codeine • Morphine • Phendimetrazine • Ritalinic acid • Ephedrine **NPSs** • 25E-NBOMe • N-methyl-2-AI • 25D-NBOMe	Lee et al. [38]
DI-LC-MS/MS LC-MS/MS SPE-LC-MS/MS	Spain	2024/ During 2022 and 2023	• The main urinary metabolite of cannabis, THCCOOH • Benzoylecgonine (BE) • Amphetamine • Ketamine (KET) • Methamphetamine (METH) • Cocaine metabolite • The unique metabolite of heroin, 6-acetyl morphine (6-MAM) • 3,4-methylenedioxymethamphetamine (MDMA)	Gracia-Marín et al. [39]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	Location	Year/ Sampling period	Types of illicit drugs & NPSs	First author& References
LC-MS/MS	Niterói Nova Friburgo Campos dos Goytacazes Rio de Janeiro Cabo Frio Resende Petrópolis	2023/December 27, 2022, and January 10, 2023	• Ecstasy • Amphetamine • Methamphetamine • Cocaine • Benzoylecgonine • Cannabis	Ferreira et al. [40]
LC-MS/MS DI-UPLC-MS/MS HPLC-MS/MS UPLC-MS/MS UFLC-MS/MS UHPLC-MS/MS DI-UHPLC-MS/MS	-	2023/ 2020-2022	• **Cocainics** Cocaine Benzoylecgonine Cocaethylene • **ATS** 3,4- methylenedioxy methamphetamine Amphetamine 3,4- methylenedioxy amphetamine Methamphetamine • **Opioids** Heroine 6-acetyl morphine Methadone Cannabinoids Morphine Codeine Other compounds	de Oliveira et al. [41]
Liquid Chromatography-Mass Spectrometry	Spain	2023/ New Year period (from 29-Dec-2021 to 4-Jan-2022) Summer Festival (from 29 June 2022 to 12 July 2022)	• Phenethylamines • Cathinones • Opioids • Benzodiazepines • Plant-based NPS • Dissociatives methamphetamine • MDA • MDMA • Ketamine • Heroin • Cocaine • Pseudoephedrine	Rousis et al. [42]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	Location	Year/ Sampling period	Types of illicit drugs & NPSs	First author& References
LC-MS/MS	Australia Belgium Brazil Cyprus New Zealand France Greece Italy the Netherlands' Iceland Spain Sweden Slovenia The Republic of Korea United States	2023/ New Year period in three consecutive years (2019–2020, 2020–2021, and 2021–22)	• Eutylone • Mephedrone • Mitragynine • N-ethylhexedrone • 2F-deschloroketamine • 3-MMC • Etizolam (Xanax) • Clonazolam • Para-methoxyamphetamine (PMA) • Pentylone • N-ethylpentylone • N-ethylhexedrone • Methylone • Methoxetamine • Methiopropamine • Mephedrone • Methylenedioxypyrovalerone (MDPV) • Eutylone • Ethylone • 4-Methylethcathinone (4-MEC) • 4-Fluoroamphetamine • 3-Methylmethcathinone • 2F-Deschloroketamine (2F-DCK)	Bade et al. [43]
LC-MS/MS	Southwest China (156 WWTPs in 21 different cities)	2023/ from October to November 2021	• Methamphetamine • Morphine • Ketamine • Codeine • Heroin	Wang et al. [44]
Solid Phase Extraction and Ultra-High Performance Liquid Chromatography coupled to tandem mass spectrometry	Eleven-time points in Reykjavik	2022/ from 2017 to 2020	• Amphetamine • Cocaine • Cannabis • Methamphetamine • 3,4-methylenedioxymethamphetamine (MDMA)	Löve et al. [45]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	**Location**	**Year/ Sampling period**	**Types of illicit drugs & NPSs**	**First author& References**
LC-MS/MS	Australia Entire population of a prison in Australia	2022/from March to December 2020	• Amphetamine • (Metabolite of methamphetamine and dexamfetamine, an attention-deficit hyperactivity disorder (ADHD) medicine; also used as an illegal drug), • 3,4-methylenedioxy-N-methylamphetamine (MDMA) • 3,4-methylenedioxyamphetamine (MDA) • Mephedrone • Ephedrine • Methamphetamine • Methylone • 3,4-methylenedioxy-N-ethylamphetamine (MDEA) • Tetrahydrocannabinol (THC) and its metabolite 11-nor-9-carboxy-Δ−9 tetrahydrocannabinol (THC COOH) • 6-Monoacetylmorphine (6-MAM), ketamine, and its metabolite nor-ketamine • Cocaine and its metabolite benzoylecgonine •	Wang et al. [7]
LC-HRMS	All states and territories in Australia, and both metropolitan and regional areas	202/ Bimonthly from October 2017–June 2018 and October 2019–February 2020	• 4-FA • Butylone • Ethylone • Mephedrone • Methoxetamine • 4-MEC • 3-MMC • Pentedrone • N-ethylpentylone • Methylone • PMA • Alpha PVP • Methiopropamine • Pentylone	Bade et al. [46]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	Location	Year/Sampling period	Types of illicit drugs & NPSs	First author& References
Solid-phase extraction, LC-MS/MS	Brasília	2022/ from March 1st to 15th 2019	• Benzoylecgonine (BE) • 11-nor-9-carboxy-Δ9-tetrahydrocannabinol (THC-COOH) • Cocaethylene (COE) • Cocaine (COC)	Sodré et al. [47]
Solid-phase extraction, LC-MS/MS	Turkey (11 cities) Adana, Ankara, Diyarbakır, Erzurum, Gaziantep, Kayseri, Konya, Mersin, Şanlıurfa, Trabzon, Van	2021/Between March 2019 and December 2019 (for a week)	• Marijuana • Heroin • Amphetamine • Cocaine • Ecstasy • Methamphetamine	Daglioglu et al. [48]
LC-MS/MS	Western United States- One micropolitan (Site A), and one rural (Site B)	2020/ April 2019 to June 2019	• Amphetamine • Morphine • 6-acetyl morphine • Codeine • Hydromorphone • MDA • Benzoylecgonine • Fluoxetine • Hydrocodone • Oxycodone • Ketamine • EDDP • Noroxycodone • Tramadol • Ritalinic acid • MDMA • Methamphetamine • Methadone	Bishop et al. [49]
LC-MS/MS	Adana	2022/ During Ramadan 21–27 May 2019	• Cocaine • 3,4-Methylenedioxy methamphetamine • Heroin • Marijuana (THC) • Alcohol • Amphetamine • Nicotine • Methamphetamine • Ecstasy	Guzel, E. [50]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	Location	Year/ Sampling period	Types of illicit drugs & NPSs	First author& References
LC-IMS-HRMS	March-June 2019	2023/ Two Slovenian municipalities; the capital Ljubljana, and a smaller one (M1).	• 3-MMC • 1R-2S-(−)-Ephedrine (licit) • Ethcathinone (licit) • 5-IT • AMT N-methyltryptamine (licit) • Ephedrine • 6-IT (licit) • 3-MEC • Pentedrone • 4-chloro-α-PPP (licit) • Isopentedrone • 2,3-DMMC • N- Ethylbuphedrone • 2-NMC • N-acetylmethamphetamine (licit) • Levorphanol • Embutramide (licit) • Kavain (licit) • 2,4-DMMC • 4-MDMC • 2-MEC • 4-MPH	Verovšek et al. [51]
LC-MS/MS (Solid-phase extraction)	Centro, Mangue, Catumbi, Alegria, Faria-Timbó and São Cristóvão	2020/ Between the spring period (September/2018) and early summer (December/2018) a	• Cocaine (COC) • Methamphetamine (METH) • 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH, THC metabolite) • Benzoylecgonine (BE, cocaine metabolite) • Amphetamine (AMP)	Pacheco et al. [52]
LC-MS/MS (Sciex 5500 + QTRAP) with an electrospray ionization (ESI) interface coupled to the HPLC system	Southern China	2020/ from November 2017 to October 2018	• Amphetamine • Methamphetamine • MDMA • Methylone • Ketamine • Norketamine • EDDP • Codeine • Noroxycodone • Oxycodone • Norfentanyl • Morphine •	Zheng et al. [53]

Table 1. Analytical methods used in the detection of illicit drugs globally (Continued)

Analysis method	**Location**	**Year/ Sampling period**	**Types of illicit drugs & NPSs**	**First author& References**
Liquid Chromatography Mass Spectrometry (LC–MS/MS)	Seyhan and Yüregir Waste Water Treatment Plants	2021/ October 2016 and August 2017	• Heroin metabolite 6-acetyl morphine (6-MAM) • Amphetamine • 3,4-Methylenedioxymethamphetamine (MDMA) • Morphine • The main metabolite of Δ9-tetrahydrocannabinol (THC), 11-hydroxy (THC-OH) • Codeine • The metabolite of cannabis, 11-nor-carboxy-THC (THC-COOH), • 3,4-methylenedioxyamphetamine (MDA) • Methamphetamine • 3,4-Methylenedioxymethamphetamine (MDEA) •	Daglioglu et al. [54]
LC-MS/MS	Montana	April 15 to June 20, 2019	• Methamphetamine • Morphine • 6-acetyl morphine • 2-Ethylidene-1,5-dimethyl-3,3-diphenyl pyrrolidine (EDDP) • Codeine • Ketamine • Benzoylecgonine • Amphetamine • Methadone • 3,4-methylenedioxymethamphetamine (MDMA) • Hydromorphone • Oxycodone • Noroxycodone • Fluoxetine • Tramadol • 3,4methylenedioxyamphetamine (MDA) • Ritalinic acid • Hydrocodone	Margetts et al. [55]

3. Results and Discussion

When the World Drug Reports and National Drug Reports are examined, it has been determined that illicit drug use is becoming more widespread in the world every day. The synthesis of new psychoactive substances and other illicit drugs is increasing every day and it is becoming difficult to track these substances instantly. From this perspective, the devices used to detect illicit drugs are very essential.

The Sewage Analysis CORe Group - Europe (SCORE), a European network, was established in 2010 to regulate the approaches used in wastewater analysis and standardize methods for participating countries. Subsequently, Turkey, like many other countries, contributed to these studies. Studies have been initiated to identify the illicit drugs used, not only by analyzing wastewater but also by analyzing the illicit drugs found in syringe residues. Pioneering studies on the detection of various narcotic substances in wastewater have been conducted in the world and Türkiye, and continue to be conducted. In addition, the studies investigated the effects of various parameters such as weekdays and weekends, national holidays, seasons, musical events, and pandemics.

In this literature research covering the last years, it has been seen that various countries analyze wastewater and choose the analysis method by taking into account the illicit drug structure, metabolites, analysis time, device sensitivity, and measurement accuracy. When all the articles examined are taken into consideration, it has been determined that many devices are used. Many devices and their various features are being developed in wastewater analysis and it is seen that LC-MS/MS is more widely used in wastewater analysis among these devices.

4. Conclusion

In these studies, which have been intensively examined worldwide, especially in the last five years, the analysis of various illicit drugs has been examined. Various methods and analysis devices were examined in these analyses. LC-MS/MS is one of the most preferred devices. Its sensitivity and desired illicit drug detection facilitate its use in studies. The type of illicit drugs, metabolite of the illicit drugs, half-life, and laboratory conditions are the determining factors in analysis methods. Considering the constantly produced new psychoactive drugs, method development, improving device properties, and following the literature are critical issues.

Sensitive results and illicit drug detection play an important role in the fight against addictions. For this reason, following the current literature and choosing effective devices are among the early prevention strategies in the fight against drugs. In addition, supporting these studies with artificial intelligence and machine learning helps develop preventive studies and early warning systems.

It is of great importance all over the world for scientists to detect newly synthesized or known illicit drugs in wastewater and report them to the relevant early warning systems. The early warning system will ensure that various law enforcement agencies are informed of the illicit drugs reported, which will also increase illicit drug screening throughout the country and thus seize the illicit drug before it is used. In addition, since drug use is a public health problem, the disease burden in the country will decrease as it will be prevented from being used. Increased data sharing between public health, hospital systems, first responders, and law enforcement is needed to ensure clarity in determining drug consumption.

Acknowledgments and Funding

This work was presented at the 3rd International Karatekin Science and Technology Conference.

Declarations and Ethical Standards

The author(s) declare that they have no potential conflict of interest regarding the research, authorship, and/or publication of this article. The author(s) also state that the materials and methods used in this study do not require ethics committee approval and/or any legal-special permissions.

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